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CMS Phase 2 Tracker,

Service Channels and Services

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The objective of this Bachelor's thesis was to study and design the CMS Phase 2 Tracker services and service channels. The Tracker will receive an update on 2025 and due to this it is necessary to redesign the services and their ideology as whole.

The study was carried out as follows. Firstly, the old Tracker service design was examined and studied to find out what ideas could be reused and what should be avoided. Secondly, many preliminary designs were made to sort out the benefits of different ideas and to see which design would be a good baseline to start building on. Thirdly, a complete service distribution was carried out based on the design idea that was chosen as the baseline. Fourthly, a 3D model representation of the distribution was created to study possible conflicts with other areas of the CMS detector. Fifthly, a new space distribution for CMS barrel and CMS endcaps was proposed due to discovering that the space currently allocated for the services is not large enough. Sixthly, simulations were made to study the environmental aspects of the services to find out suitable materials for service channels that will be constraining all of the services. Finally, simulation results were examined, and proposals were made for further studies. The study will be continued in September 2018 and will be constantly evolving until the Phase 2 Tracker update has been finished.

The studies conducted for this thesis helped in the development of the Phase 2 Tracker, and the results so far have been helpful for the project as whole. It is not possible to determine yet if the distribution and 3D designs made now will remain as they are. Most likely changes need to be made due to more elements being added, or some elements being removed or changed. In conclusion the thesis proved to be meaningful, but the study still needs to be continued as the Phase 2 Tracker upgrade evolves in the upcoming years.

Keywords	Services, CMS, Particle Detector, ANSYS, Thermal simulation

Metropolia

Contents

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List of Abbreviations

CERN	European Organization for Nuclear Research.
LHC	Large Hadron Collider. The largest and most powerful particle accelerator in the world. 27km long circular accelerator. [5.]
CMS	Compact Muon Solenoid. Particle detector used for tracking high energy collisions in the LHC. Consists from many different detector layers measuring different particles to make an image of the events happening at the collision. Length 21 meters, width 15 meters, height 15 meter. The weight is approximately 14 000 000kg. [1.]
IP	Interaction Point. A collision point in space, in the center of the detector, where accelerated particle packets traveling opposite directions collide inside the beampipe, causing high energy particles to fly outwards from the IP. These collisions are measured and tracked by the detector. [1.]
PP(#)	Patch Panel. Location or space where service connections are made. Might contain connections of many different types of services. The number is defined by distance from IP relative to other Patch Panels starting from -1. For example, Patch Panel closest to IP is PP-1 and the next one would be PP0. [23.]
TK	Tracker. The innermost detector of CMS. Divided into two main sections called IT and OT. Uses silicon pixel modules mounted on carbon fiber structures to reconstruct paths of high energy particles. [14.]
IT	Inner Tracker. The innermost part of TK and the closest detector assembly from the IP. In Phase 2 it consists of 3 different sub detectors. TBPX, TFPX and TEPX. [2.]
OT	Outer Tracker. The second detector layer of CMS. In Phase 2 it consists of 3 different sub-detectors. TBPS, TB2S and TEDD. [2.]
ECAL	Electromagnetic Calorimeter. The third detector layer of CMS. [1.]

HCAL	Hadron Calorimeter. The fourth detector layer of CMS. [1.]
VAC-Tank	Vacuum tank containing the superconducting coil of CMS magnet. Fifth layer of CMS. Supports all detector layers inside it. [15.]
YB0	The main structure of CMS Barrel, supports the VAC-tank. Contains also one wheel of Muon-chambers used to detect muons. Weighs approximately 2 000 000kg when empty. [16.]
OD	Short for Outer Diameter. Generally used for describing cables, pipes or round objects size.
ID	Short for Inner Diameter. Generally used for describing the size of the inside of a pipe or a round object.
PCB	Printed Circuit Board. A circuit board used in electronic hardware.

1 Introduction

Compact Muon Solenoid, CMS, is a high-energy physics experiment located at CERN. Its main purpose is to record collision events that occur in CERN's Large Hadron Collider, LHC. First taken in use in 2008, CMS consists of many different sub-systems, each dedicated for a different purpose. In this thesis, the focus will be on the innermost part of the CMS detector, called the Tracker. The Tracker itself is divided into two main sections called the Outer Tracker and the Inner Tracker. These main sections are built from smaller assemblies that contain particle detector modules used for measuring the paths of particles traveling through CMS. Visualization of the CMS experiment can be seen in Fig. 1. [1.]

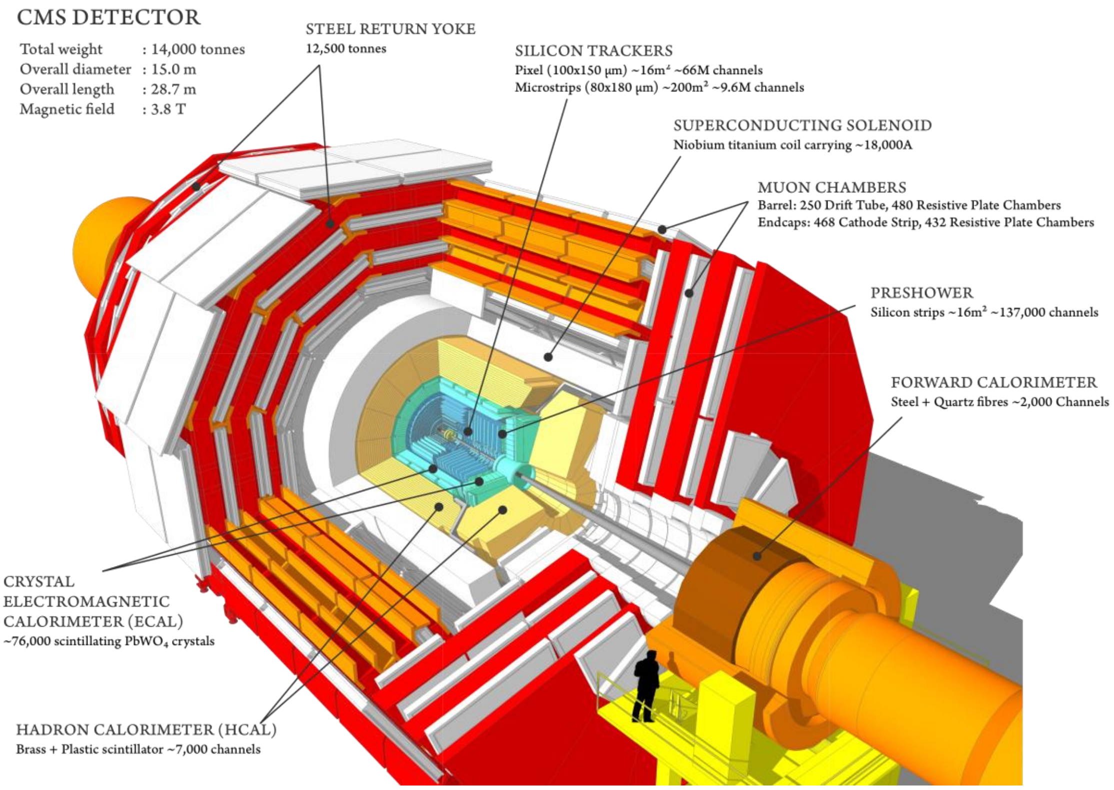


Figure 1. The CMS detector. [1]

This thesis examines the services and service channels of the CMS Tracker. The existing CMS Tracker will be replaced in 2025 by a new one, in the so called 'Phase 2 Upgrade' [2]. The new Tracker will demand more power, more cooling and higher data transfer rates. To meet these new requirements, an overhaul of the corresponding services and service routing is required. The present objective is to provide an initial design and a concept for all services and service channels for the CMS Tracker. This concept shall then be improved and modified in the future to accommodate possible changes in the new Tracker design.

The services of the tracker have to travel long distances from individual modules to reach the terminations (power supplies, optical driver/receiver units and cooling plants) located outside the CMS. The services paths are divided into sub-sections by patch panels. These patch panels (counted from innermost to outermost) are called PP-1, PP0 and PP1. From the last patch panel, the services will travel to their individual terminations depending on the type of service. In this thesis, the focus will mainly be on services and service channels located between the PP0 and the PP1.

2 Current design

2.1 Overview of CMS, Tracker and naming convention

CMS consist of 3 main assemblies: the barrel and the endcaps. The barrel of the CMS is stationary, and the axis of the barrel is parallel along the beam of the LHC. The barrel contains 5 different main layers of cylindrical detector elements. The innermost layer of the barrel is called the Tracker. The Tracker is used to track the trajectories of particles flying through the experiment during collisions. The collisions occur at the interaction point, IP, in the center of the experiment. The endcaps of the CMS are movable disk-like objects that are used to close the ends of the barrel. The movable design of the endcaps allows access to the different layers of the barrel. [1.]

CMS has a naming convention that is based on the IP and the round shape of LHC. As the barrel lies with its center axis along the beam of the cylindrical LHC, the side of the barrel that is located inside the LHC circle is called NEAR. The opposing side is called FAR. [17.]

If the round LHC is looked at from the top and the CMS barrel is divided into two ends divided by the IP, the part of the barrel in the clockwise direction of the LHC circle is called -END and the part of the barrel in the anticlockwise direction is called +END. Fig. 2 displays the LHC complex and different detectors. [17.]

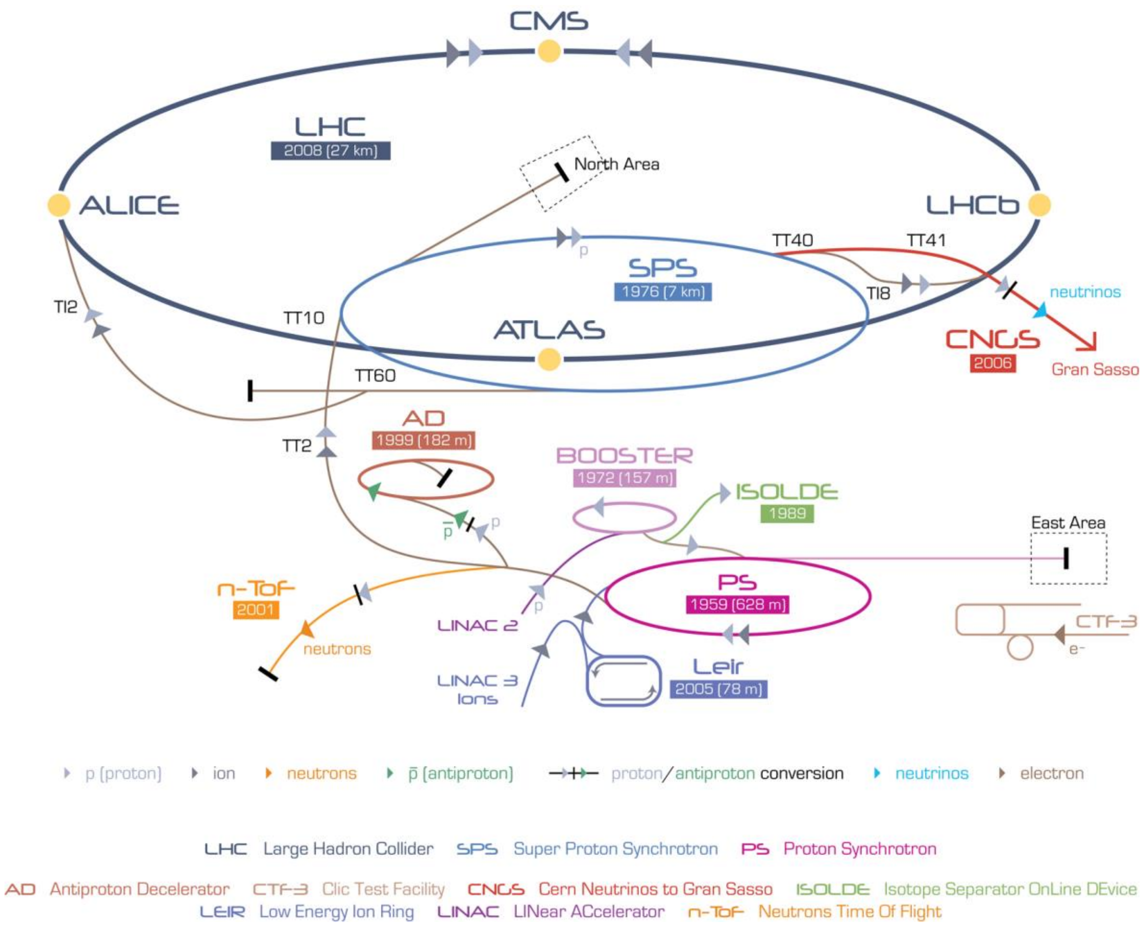


Figure 2. CERN accelerator complex. [3]

If the cylindrical CMS barrel is looked along the beam from the +END towards the IP, the barrel appears circular. Anything located along PHI of any given radius of the barrel is named or counted anticlockwise. The counting begins from the right side of the horizontal axis, or simply put from the 3 o'clock position. This convention is push through symmetric to the -END of CMS. It means that if we look from the -END towards the IP, the counting is clockwise and starts from the 9 o'clock position. [17.]

The naming convention is global for CMS and applies to everything inside the detector. By applying this naming convention to the Tracker, it is divided it into 4 sections, +END NEAR, +END FAR, -END NEAR and -END FAR. [17.]

The CMS global coordinate system has its origin in its center, at the LHC beams' interaction point, IP. The positive Z axis of the axis system is parallel to the beam, and pointing counterclock-wise (towards Jura mountain) when looking at the LHC ring from above. The X axis is horizontal and points towards the center of the LHC. The Y axis is vertical axis and points upwards. As the LHC tunnel is tilted from the true horizontal plane, the beam and therefore also CMS are tilted by 1.23%, such that there is an upwards slope towards Z+ direction. The CMS Y+ is consequently also tilted by 1.23% from the true vertical. In the design work, this tilt angle is taken into account in a tilt in gravitational loads. [2] The Tracker is approximately a 6 meters long barrel with an OD of 2.5 meters, and it is divided into two parts, the Inner Tracker (IT) and the Outer Tracker (OT). Both of these contain several barrel and disk shaped sub detectors. The IT barrel is the innermost barrel of the two and it is designed to be removable and replaceable during technical stops of the LHC. [2]

2.2 Current Tracker service design overview

In Fig. 3 the outer shape of the Tracker Support Tube can be seen inside the central YB0 structure of CMS. This is the structure within which all the Tracker sub-detectors are located. The services of the Tracker are routed out from the Tracker volume by following the surface of the YB0 until the services are out of the detector volume. Between the Tracker and the outside there are two patch panels for the Tracker services.

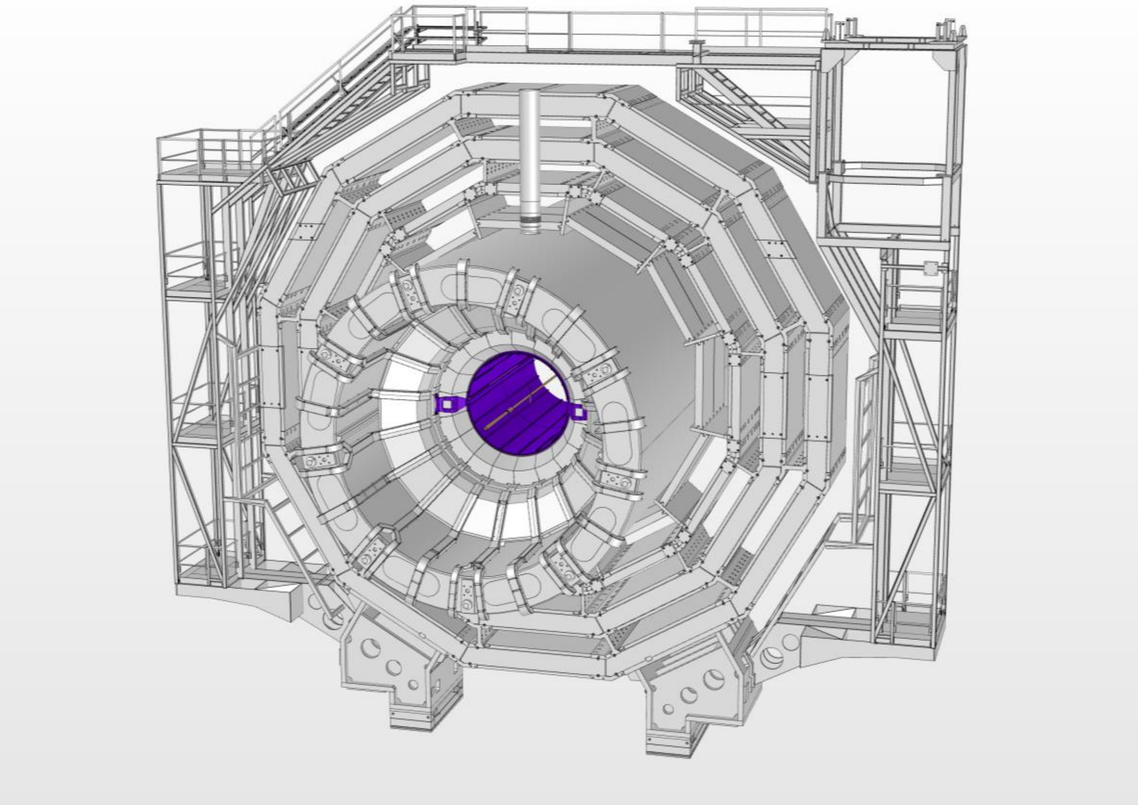


Figure 3. View of the YB0 and VAC-tank with the periphery of Tracker in purple and the Beampipe in brown.

For the Inner Tracker, the first patch panel outside the Tracker volume is named PP0, and it is located 2.75m away from the IP along the beamline. There are two of these patch panels in the Tracker, one in each end of the Tracker, and are supported by the Bulkheads located at the Tracker ends. The Bulkheads are disks, with a diameter of 2 meters, where services and connections are mounted on. This patch panel PP0 is essential for the installation of Inner Tracker as it ensures a minimum length of services hanging out from the IT while it is installed. The Bulkhead can be seen in Fig. 4.

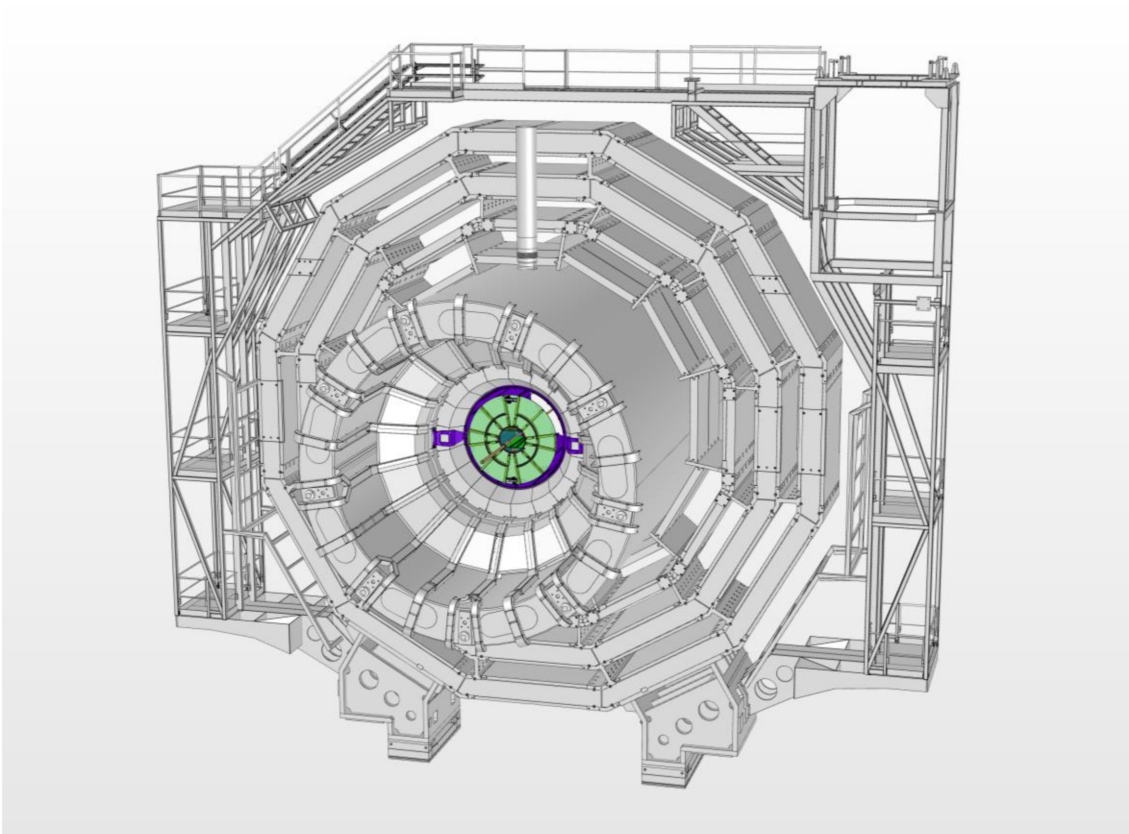


Figure 4.   Displays the Bulkhead in green.

The next patch panels further out from the IP are called PP1s. The PP1s are located on the inner surface of the CMS magnet’s cryostat wall. (yellow objects in Fig. 5). In total there are 32 PP1s in the whole CMS, 16 per end. All services of the Tracker have a connection at PP1. At this connection, depending on the service type, piping, fibers or cabling are switched to more optimized types due to space limitations between the PP0 and PP1.

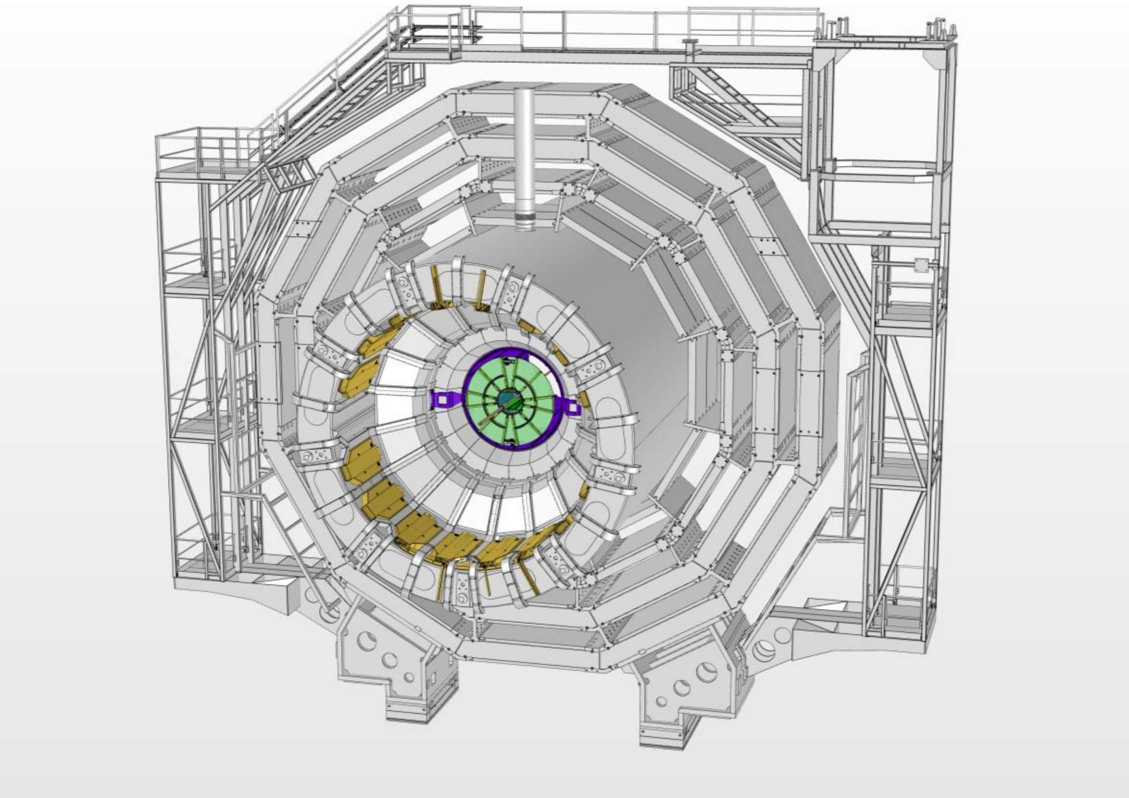


Figure 5. Displays PP1s in yellow.

Between the PP0s and the PP1s there are service channels where all the services of the Tracker will run. The service channels are divided into 5 sections along the full length of the service channel with a different aspect ratio and orientations for each section. Sections are counted from the IP outwards. The service channels are illustrated in Fig. 6. The division of each service channel to 5 sections can be seen in the Fig. 7.

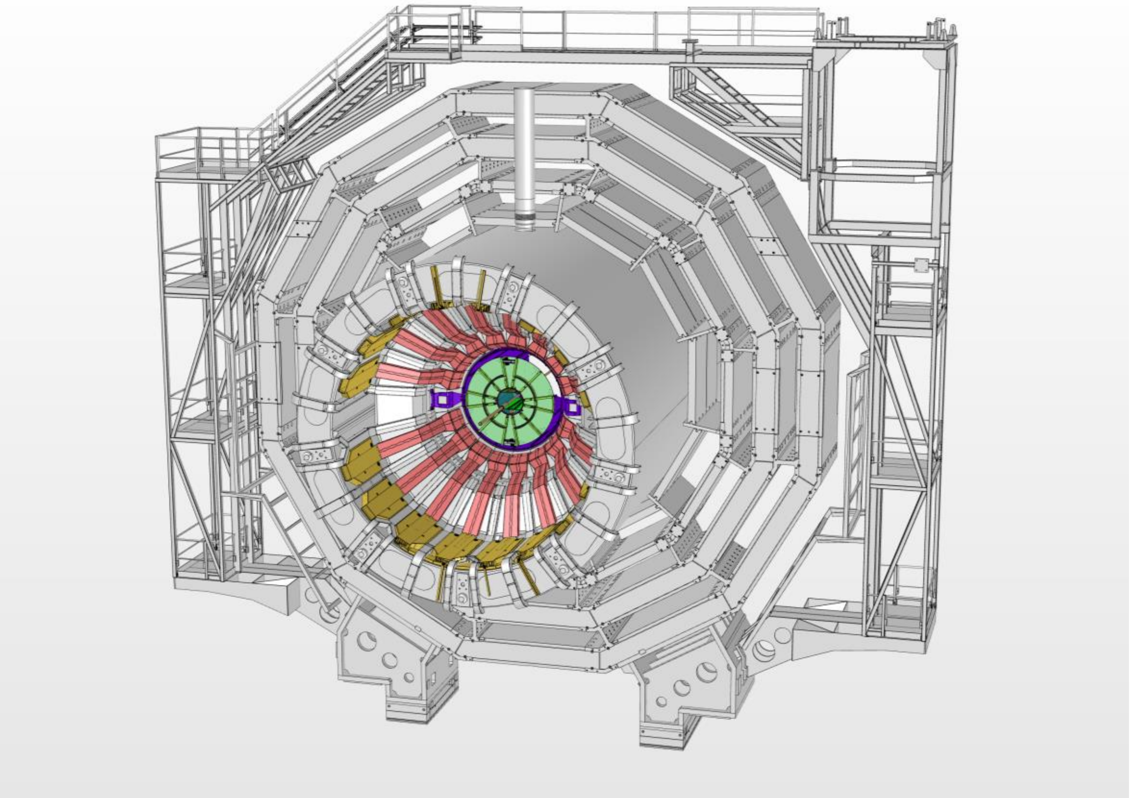


Figure 6. Displays the Service channels in red.

Also each section is divided into 3 sub-sections to keep different service types separated from each other. In total, there are 32 Tracker service channels in the CMS, 16 per end of CMS. Currently these channels are made out of stainless steel.

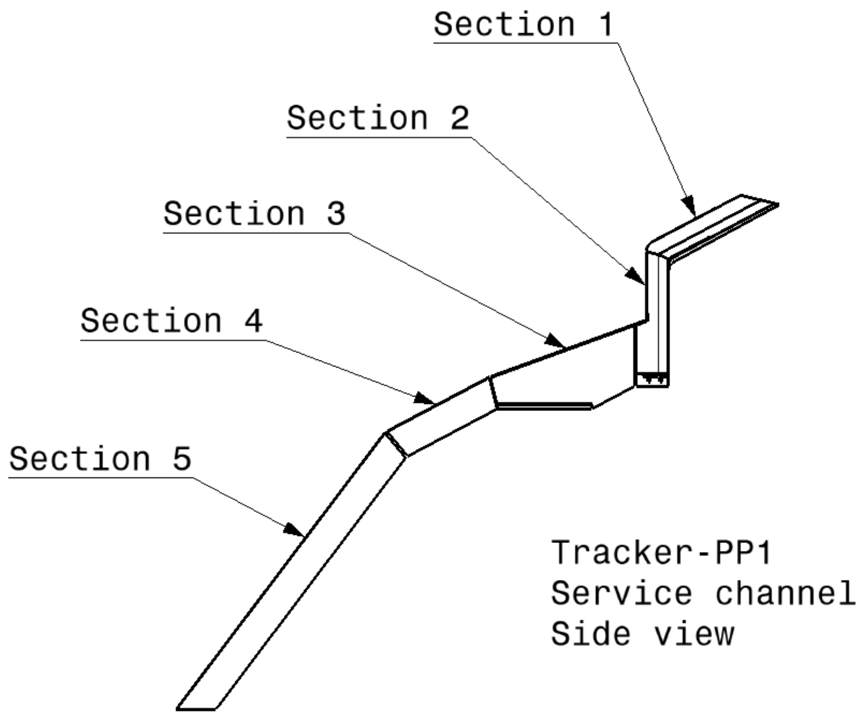


Figure 7. Service channel side view with sections

The old service design has several limitations due to various reasons. The first being that the original Tracker service design was done some time ago, and after that the IT has been updated with new internals in spring 2017. The services for the upgraded IT had a very limited amount of space. This was caused by being limited to the old service distribution, and due to some of the older installed services being unremovable at the time of the upgrade. The second limiting factor is the size of Section 1 and Section 2 of the service channel. The old service channels and PP1s were designed for a certain number of services that fitted when it they were originally installed, but due to an increased quantity of elements inside the Tracker, the installation of upgraded IT was on the limits of the channel and PP1 capacity. At this time it was impossible to modify the dimensions of the Sections. This led to a situation where the channels and PP1s were in some cases closed by force after the installation was finished. [18.]

Due to the channels being made from stainless steel, the material properties of the channels were not sufficient from a thermal point of view. After the first tests it was noticed that the insulation around the pipes was not enough to keep the channels at a reasonable temperature to prevent condensation on the surface of the channels. The channel sections containing cooling pipes for the Tracker had to be heated up with water circulation, but since the channels were made of stainless steel, also copper plates had to be added to conduct the heat from the water circulation into the sections. Afterwards it was discovered that the water circulation was not enough, and therefore power cables were mixed into the sections with the cooling pipes and heating coils were also added to prevent condensation in difficult. All these additions made the already limited space for the services inside the channels even tighter. [18.]

Figure 8. Mockup of Phase 1 service channel

In Fig. 8 it is possible to see a mockup of the old service channel without cover plates and covering insulation. Green cables are the power cables for the Tracker, and copper pipes are the cooling pipes for the Tracker.

2.3 What ideas can be reused

The current concept of where the Tracker patch panels are located and how it allows testing and the installation of various sub-assemblies separately is well designed. For Phase 2 the same principle will be kept, although the locations for OT PP0's will be different due to OT sub-assemblies being different. For IT, the Bulkhead will remain as the PP0. This arrangement of patch panels also ensures that services can be optimized between different patch panels for optimal space consumption, durability or losses. For example, the cooling pipes coming from outside up to PP1s are vacuum jacketed pipes to ensure good insulation, but from PP1 onwards in to the Tracker, the piping is more traditional copper or stainless-steel piping with ARMAFLEX insulation wrapped around. The power cables respectively switch from thick low cost, high efficiency cables to thinner and more expensive cables with higher power losses.

One of the basic ideas is to have a slack accommodation of all cables and fibers of the Tracker inside the PP1 to reduce the mass and space consumption inside the tracker volume. The way how power cables and optical cables are connected at the PP1 with the slack taken into account has also proven to work well enough, although there were some problems with the PP1's being slightly overcrowded during Phase 1 upgrade. [18.]

In more detail inside one PP1, the power cables are connected into PCB's to switch from one cable type to another. To take into account the power cable slack, a U-turn is made inside the PP1 before the connection, and in this way the slack is automatically eaten by the U-turn being a bit longer or shorter depending on the length of the cable.

For optical fibers, the connection and the slack accommodation are carried out differently. The optical fiber connections are placed on slide-able trays that allow the connections to be made easily while the cables are held in position. These trays also have space reservation for the slack of the fibers. The slack is eaten simply by curling the cable in to a shape of number 8 before connecting.

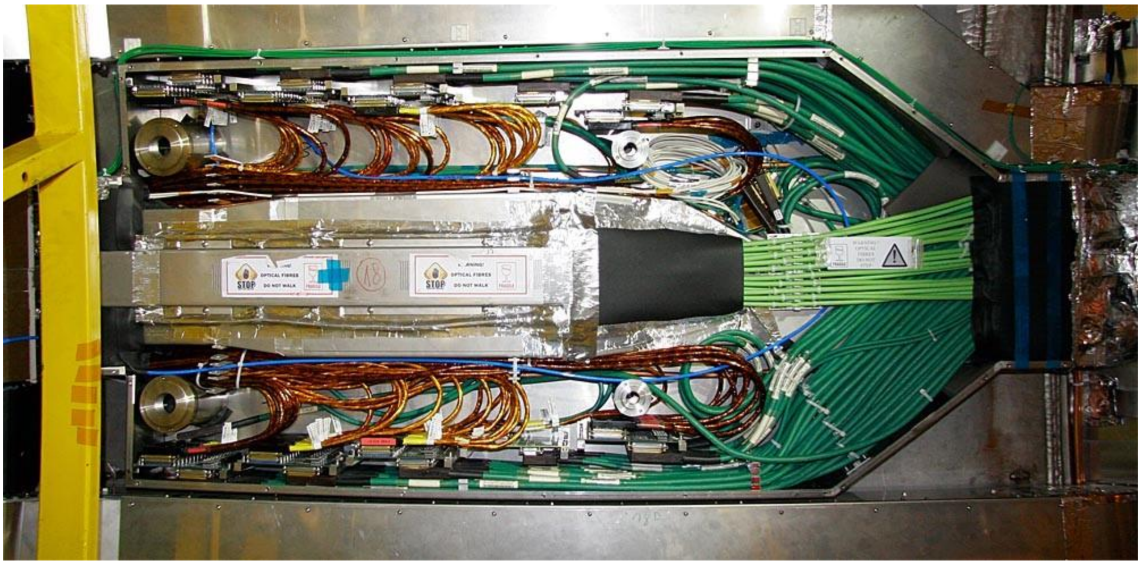


Figure 9. Image of Phase 1 PP1 with services. [3]

In Fig. 9 the contents of Phase 1 PP1 are shown. The left side is towards the IP, and the right side is towards the endcap of the CMS. The dark green cables coming from the right are power cables that are optimized for low losses along the long distance that they travel. In the ends of the dark green cables there are the PCBs where power cables are connected. The copper colored cables are the space optimized power cables that travel in the service channels into the Tracker. The U-bend mentioned earlier can be seen immediately after the connection. In the middle, there are light green cables, these are the optical fiber bundles coming from the outside. The bundles go into the box seen in the middle, where the bundles have connections for switch to space optimized ribbons. On both sides of the optical fiber box, a pipe covered with aluminum tape can be seen. These pipes are the water circulation loop that travels up and down the service channel. Inside the PP1 also cylindrical posts can be seen, these are actually attached through the PP1 into the VAC-tank. These provide mounting possibilities for different assemblies like walking platforms or installation tools. [18.]

2.4 What needs to be studied

Although the basic concept of services is good, there are various details that could be improved. To start with, the channels thermal properties should be taken into account in the new design. As mentioned before, in the service channels the cooling pipes were mixed with power cables, and heating coils were added in attempt to heat up the channels. This is an inefficient way to achieve sufficient delta to achieve desirable temperatures. To make the channel design for cooling even more efficient, it could be beneficial to have the insulation built in to the channel in a way, that during installation of pipes all the insulation is already in place, and pipes are simply placed into the channel and closed/sealed in.

The distribution of space also needs to be redefined, especially since in Phase 2 the ratio of services between IT and OT will be very different. In Phase 2 the amount of IT services relative to OT services is significantly more than before.

Overall, there will be more services than before, and to ensure that these services will fit into the service channels further examination is needed. The channel cross sections need detailed planning.

3 Phase 2 Design

3.1 Service design basic concepts

As already described shortly, the first of the cornerstones of the Phase 2 design is to keep the concept of having two main patch panels, PP0 and PP1 for the Tracker services. They will serve the same purposes as in Phase 1. PP0 will be used for making the installation and testing of individual sub-detectors possible. In PP0 the aim is to have as little slack of the services as possible since it is necessary to keep the weight and space consumption to minimum inside the Tracker volume. As PP1s are located outside of the Tracker volume at the periphery of VAC-tank, they will be used for slack absorption and as place for switching from cost effective services to more optimized and expensive services when entering the volume inside the VAC-tank.

The second cornerstone of Phase 2 design is the Service channels that will run between the PP1 and the PP0. Their purpose is to separate the services of the Tracker to be in their own controlled environment. Another purpose for the service channels is to provide support and controlled routing for the services since they need to stay inside a predefined envelope to make sure that it is possible to close and operate CMS. If the envelopes are not respected, there is a risk of colliding the movable endcaps of CMS with the barrel of the CMS. Even if there is no collision during the closure, it is still possible to have a collision after the magnet of CMS is turned on, as the 4 tesla magnetic field compresses the whole 14,000-tonne experiment by some centimeters.

In addition to Tracker services, a new detector layer called BTL will be introduced inside the Tracker volume. The services of the BTL will be routed with Tracker services. At this point the service amounts are unclear, and a reservation of services for BTL is estimated based on the power consumption of the BTL.

3.2 Service amounts and types

In general there are three main service types, power, cooling and optical. In addition to these services a series of environment sensors and dry gas injection pipes need to be routed into the TK volume to control and measure the gas volume.

3.2.1 Power

For power there is a cable proposal from the Electronics section that will be assumed as the universal cable used for the whole Tracker and BTL for now. In reality this cable or a variant of it is most likely used only for OT, but for the general calculations for space consumption it works well as IT and BTL cables will most likely have the same or smaller cable OD. In more detail this proposed PE-jacketed cable with an OD of 13.4mm for OT, contains twelve low voltage power links and thirteen high voltage wires used for powering the tracker silicon modules.

For this study, the Electronics section has also provided the estimated amounts of cables needed for the OT and IT based on the amount of silicon modules that are proposed for the Phase 2 tracker. OT is estimated to require 1224 of the proposed power cables, and the IT is estimated to require 332 power cables that are not yet specified in more detail. In total approximately 1556 cables are needed for Tracker.

For power cables having a connector that is robust, but also fast and easy to use is required as some parts of the detector are radioactive after the detector has been used, and it is important to make sure that everyone can do their work quickly to get as small a radioactive dose as possible. Keeping the previously mentioned constraint in mind, for this study the size 5 D-SUB connector that was proven to work well in Phase 1 was chosen as the proposed connector that would be used with all cables. This connector would have a custom molded boot that ensures minimum space consumption and allows directing the cable to wanted direction after connection. The connector is extremely durable and relatively easy and fast to use.

Figure 10. D-Sub size 5 connector with custom molded boot.

Fig. 10 displays a custom size 5 D-SUB connector that was used during the Phase 1.

3.2.2 Cooling

For cooling there were no detailed designs available at the time when this study was carried out. It is known that the cooling system will be based on two phase CO2 cooling for cooling the Tracker. Based on the Tracker power consumption of 100kW and the amounts of different sub detectors, it was estimated that the Tracker would need 66 cooling loops, 46 for the OT and 20 for the IT. Between the PP1 and the PP0 it was estimated that with these loop amounts, the inlet cooling line would have an ID of 6 and OD of 8, and the outlet cooling line would have an ID of 12 and an OD of 14. These estimates were done by an experienced cooling engineer to have a baseline for starting this study of services. The connection of these pipes is assumed to be done with VCR connections as they are widely tested and proven reliable and easy to use.

From outside to the PP1 the cooling will arrive in vacuum jacketed transfer lines that will be connected to the aforementioned pipes inside the PP1. At PP0 the pipes will be connected to manifolds that distribute the cooling to module cooling loops. The pipes running in the service channels between the PP1 and the PP0 need to be insulated. For insulation 25mm of Armaflex insulation was chosen as the starting point. [19] The effectivity is studied, and optimization of the insulation will be done later-on in this study, after the space limitations are known.

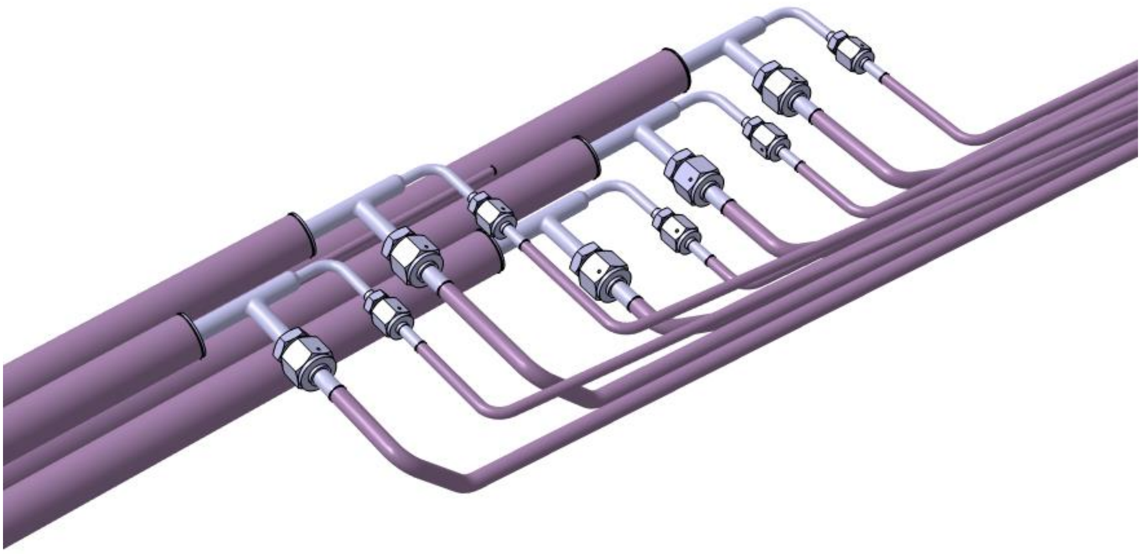


Figure 11. VCR cooling pipe connections with vacuum jacketed pipes.

In Fig. 11 it is possible to see a 3D-model of the vacuum jacketed pipes (left), the VCR-connections (middle) and the normal copper pipes (right).

3.2.3 Optical fibers

There will be three different styles of optical fiber cabling running from the tracker to outside of the CMS barrel. From outside to PP1 the fibers will arrive in a Trunk cable that has an OD of 9mm. Inside PP1 boxes the Trunk cables are split with a fanout kit that separates the Trunk cable into 6 individual fiber bundles. Each of these bundles has an OD of 3,6mm and each one contains 24 individual fibers. These bundles run from the

PP1 to the PP0 and after PP0 separate to individual fibers. MPO connectors were chosen as the suitable connector to use in the PP0 and PP1 as the connectors are easy and fast to use. Approximately 1420 fiber bundles are needed for the whole tracker. 124 of these will be for IT and 1296 for OT.

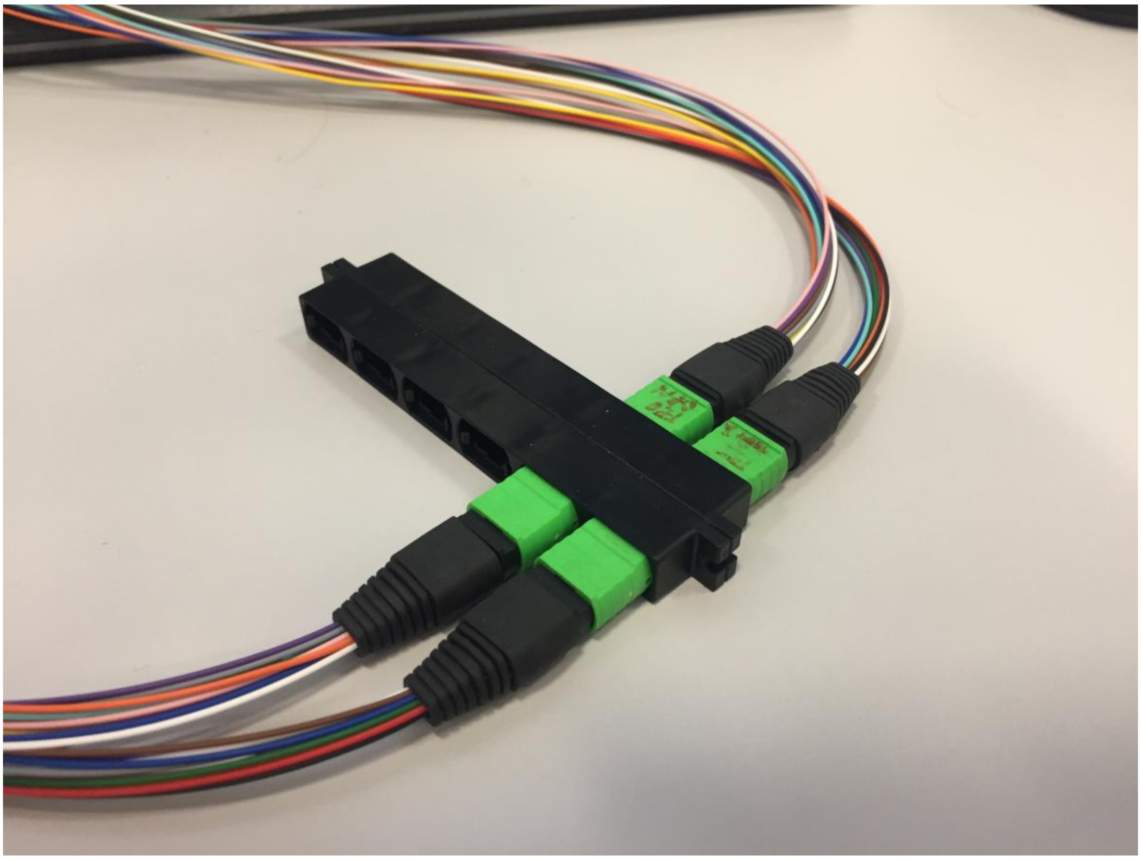


Figure 12. Short boot MPO connectors with a MPO to MPO adapter.

Optical fibers are among the least space consuming services inside the service channels as the diameters of the fiber bundles are small. The real space consumption of the optical fibers comes from the fact that the fibers are relatively easily crushed and the fiber bundles need to be protected from the rest of the services. This means that one sub-section of the service channels will be reserved for the fibers only. It is also good to note that the Optical Fibers are thermally neutral. In Fig. 12 it is possible to see these small individual fibers that would normally be covered by thin flexible tube.

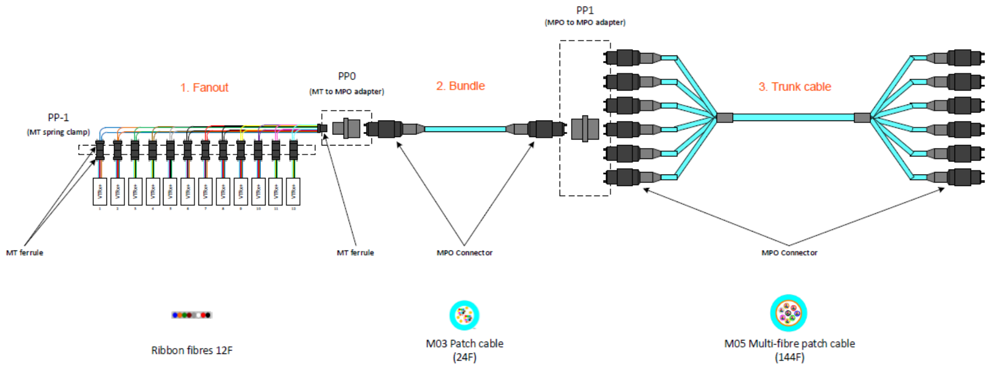


Figure 13. Optical fiber cabling scheme. [May 2017, Meeting]

In Fig. 13 the connection scheme for the optical fibers is shown. This displays what kind of connections and cables will be used between different patch panels.

3.2.4 Other services

For the upkeep and inspecting the environment inside tracker, several other services are also needed. These services consume relatively small amount of space among cabling, cooling and fibers, but are still essential to take into account when looking at the space limitations of the services. These services include dry gas injection pipes, sniffing pipes and environment sensors like humidity sensors and temperature sensors. [20.]

The function of the dry gas injection pipes is to feed dry gas into the tracker volume to help keep the humidity of the gas volume as low as possible. These dry gas injection pipes will have an OD of 6mm and there will be 96 of these in total. 24 for IT and 72 for OT. [20.]

Environment sensors used for tracking the gas volume inside the tracker are essential for operating the detector as they collect real time data for the operators. The cabling or wires for these sensors have an assumed general OD of 3mm and the amount of cables or wires needed is approximately 236. 72 for IT and 164 for OT. [20.]

The environment sensors inside the Tracker are limited in size and mass due to space constraints. The low operating temperatures of the Tracker makes tracking the environment demanding. Due to the difficulty, sniffing pipes are used to take samples of the gas volume inside the Tracker and bring them outside of the experiment for highly precise measurements in industrial sized sensor machines like cold mirror humidity sensors. 26 of these pipes will be needed and the assumed OD is 6mm. 10 pipes for IT and 16 for OT. [20.]

3.3 Service channels

All of the services for the Tracker have to run through 32 service channels to reach the Tracker volume. 16 of these channels are located at the +END and 16 are located at the -END. The channels are spread evenly around the center axis on both ends, but the horizontal axis is avoided as it contains the support brackets for the Tracker. The counting of these channels begins from 2 as the first slot along the horizontal line is occupied by the bracket. To make the distribution of the services easier to understand, the channels also are given names like OT1, IT1 and OT2 etc. depending on what services they contain.

One service channel is divided into five sections. The sections are counted from the IP outwards, so the section closest to the IP is called Section 1. In Phase 1 each of the sections are divided into three sub-sections, and the baseline for Phase 2 is to keep the same design but redistribute the sub-section space allocations to suit the Phase 2 services better.

The current service channels are made out of stainless steel, and as previously described this was unideal as the thermal properties were sub-optimal. Later in this thesis after a good distribution of services has been found, the material choice for the channels will be studied with ANSYS simulations to find out a suitable material for the Phase 2 channels. Already it has been decided that the water loops that were installed during the Phase 1 should be also included in the Phase 2, and the amount of water loops per channel should be increased. Currently, there is only one water loop per channel.

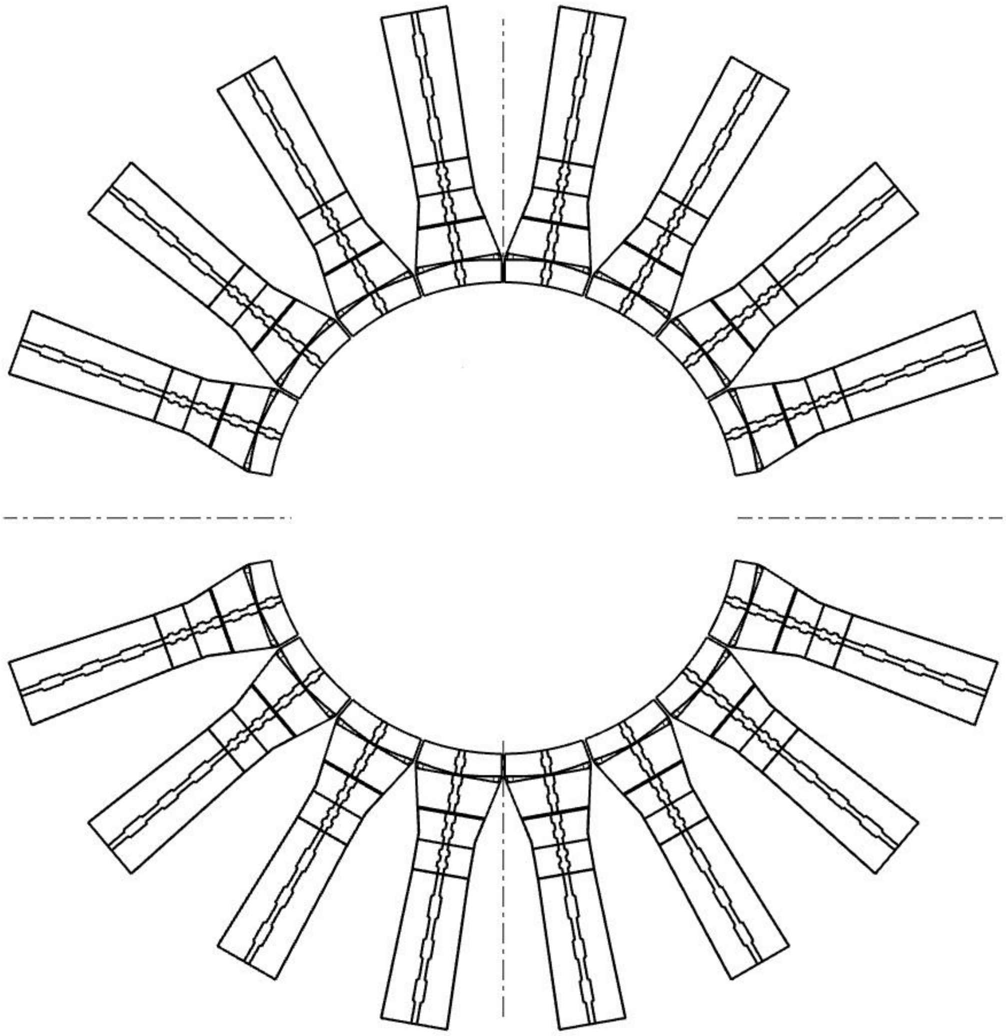


Figure 14. Service channels of one end.

Fig. 14 displays the arrangement of service channels in one end of the CMS.

3.4 New service mapping

New service mapping is done based on the service input listed earlier, and changes to this might need to be done later, as the design of the Tracker sub detectors is still under modifications.

3.4.1 Simple division of required services.

By taking the total amount of services for IT and OT, and comparing the IT and OT service amounts to the total amount of services, we can get an idea of how many channels should be given for IT and OT. As cables are the biggest and most space consuming service, they are used as the cornerstone for this comparison. The total amount of power cables was 1556 and the amount of OT cables was 1224, so the OT cables take up 78% of the total amount. In one end there are 16 channels. 78% from 16 channels equals to 12.5 channels, but the IT and OT services need to be kept in their own channels and it is beneficial to keep the number of channels even, so the number I rounded down to 12. It means that in total there will be 24 channels for OT and 8 for IT, 12 OT and 4 IT per end. From this information it is easy to extract a preliminary table of services per channel. Before doing the extraction of the table, the power cables are grouped depending on their purpose to make the table more detailed. For IT the power cables are split to three groups. The groups are 2-chip modules, 4-chip modules and LpGBT boards. For OT the power cables are split to 2S and PS modules.

Table 1. Preliminary distribution of services to channels

Service type	IT	OT	IT+	OT+	IT+, HALF	OT+, HALF	IT ONE CHAN-NEL	OT ONE CHAN-NEL	OD (mm)
Power cables IT 2 chips	136	0	68	0	34	0	17	0	13.4
Power cables IT 4 chips	156	0	78	0	39	0	19.5	0	13.4
Power cable LpGBTs	40	0	20	0	10	0	5	0	13.4
Power cable OT PS	0	582	0	291	0	145.5	0	24.25	13.4
Power cable OT 2s	0	642	0	321	0	160.5	0	26.75	13.4
MFB	124	1296	62	648	31	324	15.5	54	3.6
Inlet cooling pipes	20	46	10	23	5	11.5	2.5	1.9	8
Outlet cooling pipes	20	46	10	23	5	11.5	2.5	1.9	14
Dry gas injection pipes	24	72	12	36	6	18	3	3	6
Sniffing pipes	10	16	5	8	2.5	4	1.25	0.7	6
Environment sensors	72	164	36	82	18	41	9	6.8	3
Channel water pipe	16	48	8	24	4	12	2	2	10

In Table 1, it is possible to see the preliminary split of services without any adjustments. It reveals which services are dividable by the amount of service channels reserved for IT and OT.

3.4.2 Distribution logic

In Table 1 a rough split of services into channels can be found. Now this split needs to be adjusted since not all the services are dividable by the amount of channels, and since it is beneficial to group cooling pipes together as much as possible instead of spreading them into every channel. The reason for wanting to group the cooling pipes is the fact that the same amount of pipes require a smaller amount of insulation in total when grouped together.

Currently per END, the IT services are routed to two channels located close to the vertical axis. Since IT is supposed to be removable and replaceable, it would make sense to use the more easily accessible horizontal channels instead of the harder to reach vertical channels. Because the first slots at the horizontal axis are not available to be used for service channels, the four channels per end closest to the horizontal axis were chosen for the IT.

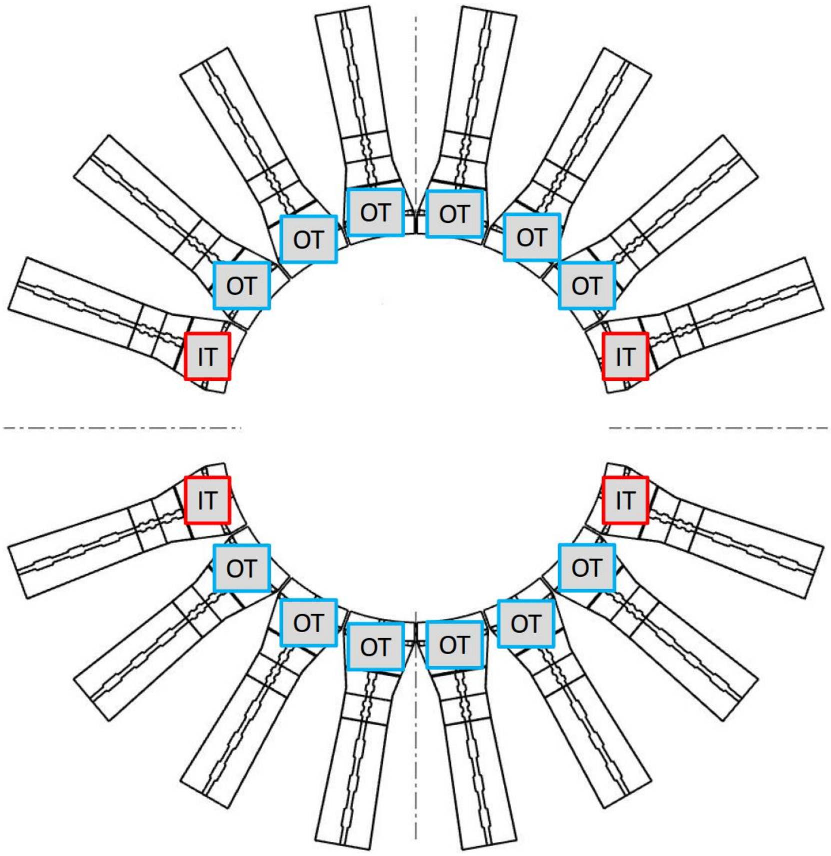


Figure 15. Service channel distribution per end.

3.4.3 Service cross sections and fill factor

The cross sections of different services need to be calculated to find out how much space they consume inside the channels. This also helps to distribute the services more evenly into the service channels.

Since the services are rigid and do not behave like a liquid, the cross section used by the services should not be calculated directly from the cross section of a single cable or pipe. This is due to the fact that the services are round, and it is impossible to pack them in such a way that a volume could be filled completely. Instead, when the cables or pipes are being packed together in a channel it is better to calculate the cross section of a cable like it was a square shaped since it more closely reflects the real space used by the individual cables or pipes when stacked together with other services.

When calculating how many services can fit inside a given area, it is also necessary to take into account the fill factor or in other words packing factor. Since the cables are laid down by a human into a channel built from multiple different shapes with sharp turns, it is almost impossible to lay the cables into a perfect stack. Due to this, even when calculating the individual round services as squares, it is necessary to limit the fill factor of the channels to 75% full to ensure that the services actually fit inside the channels in reality.

3.4.4 Calculation of service channel cross sections and fill factors

Since the service channels are built out of five different sections as shown in Fig. 7, for inspecting the fill factor of services, the smallest section of the service channel should be chosen as the reference. Cross sections for each channel were calculated, and it turned out that the Section 2 of the channel is the smallest one of the five. Also the Section 1 was also notably smaller in comparison to the 3, 4 and 5. The explanation for the smaller cross section of the two smaller sections is that they are lower in height than the rest of the sections.

Table 2. Cross sections of every section

	Section 1	Section 2	Section 3	Section 4	Section 5
Height (cm)	6	5.5	9.5	8.5	8.5
Width (cm)	40.8	35.2	32	30.5	30.5
Cross section (cm2)	240.8	189.7	304	259.25	259.25

Each of the sections are also divided into three different sub-sections. In the middle of the service channel there is a smaller sub section that is used only for optical fiber bundles as they need to be mechanically protected from other services. The two other sub sections are larger and symmetric around the middle of the channel. These two large sections are generally referred as “half channels” as the narrow middle section splits the channel into half.

Since cooling services will be grouped together as much as possible, the channel width available for pipes with insulation needs to be found out to know how many loops it is possible to fit in one half channel. To get started, the dimensions of the middle channel need to be defined first to find out how much width is left for the two half sections. Since the MFBs for the OT will be spread as evenly as possible to every channel, it is possible to construct a stack of bundles based on the number of MFBs shown in Table **1** to see how much space in width such amount of fibers would take. Before making such a stack, extra bundles need to be added to make sure that the BTL fibers that are not included in the Tracker service calculations will also fit. Since no numbers for BTL exist, it is assumed that 25% of the amount that Tracker needs would be a safe number as BTL uses 20% of the power that Tracker uses. 25% of OT MFBs equals to approximately 14 MFBs per OT channel for BTL. In total there would be 54 + 14 MFBs per OT channel based on the previous calculation. However, since the adapter that is used for connecting the MFBs at the PP1 and PP0 supports six connections it is preferable to round up the amount of MFBs to a number that is dividable with six. After taking into account all the previous factors, it was decided that one OT channel would contain 72 MFBs, some of which could be used as spares if other bundles are damaged during installation. By visually fitting 72 MFBs into the channel it was found out that 24mm wide section with 2mm wall thickness would be a good baseline for the middle section.

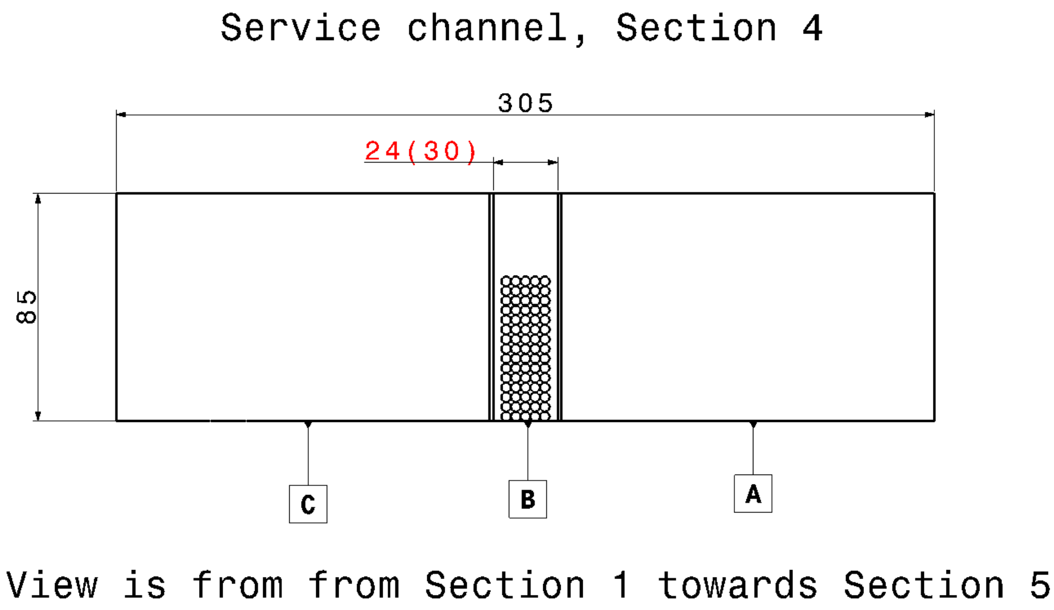


Figure 16. Middle or B-section cross section.

Now that the smallest channel cross section (Visualized in Fig. 16) has been found it is possible to start distributing the services and see if there is a problem with the fill factors. The numbers shown in Table 1 were used as a baseline for distribution. As mentioned before, the cooling pipes were grouped together as much as possible. To make the calculations a bit smarter, a stack of pipes with a realistic stacking and 25mm insulation around them was designed. After finding out a preliminary way for stacking the pipes, the stack was virtually test-fitted into one of the three sub sections of the most-narrow channel section to find out that maximum amount of cooling loops that could fit in one half of the channel with insulation is 5. This is shown in Fig. 17.

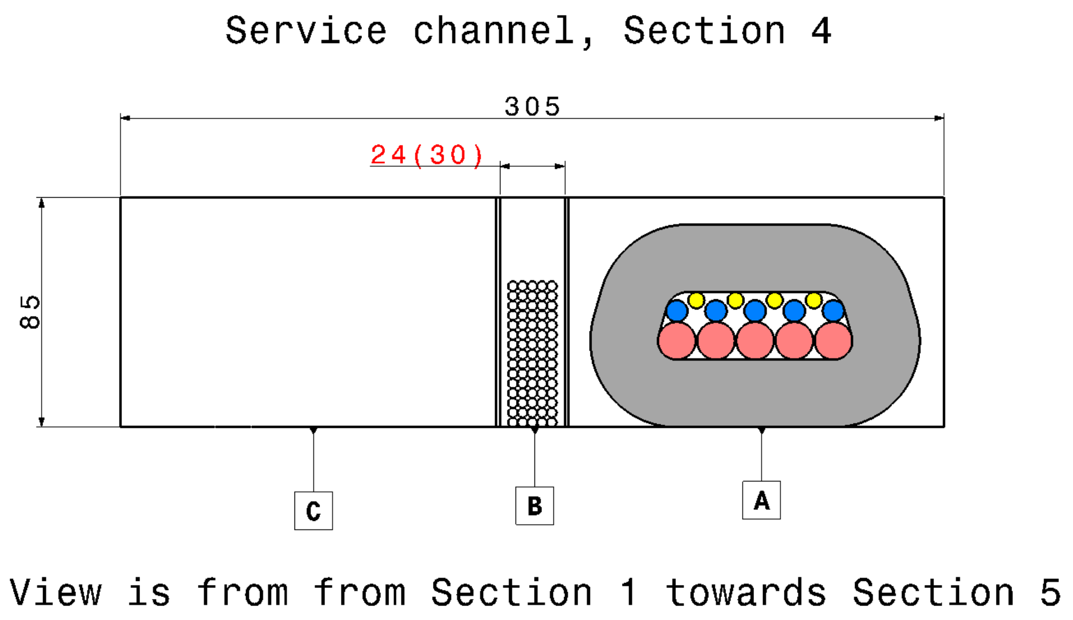


Figure 17. Bundle of 5 cooling loops inside the most narrow channel section

The required amount of cooling loops was 46 for OT and 20 for IT for the whole Tracker. Both ends of the Tracker should be as symmetric as possible, so for now focus is only on +END of the Tracker. In +END OT needs 23 cooling loops and IT needs 10. The maximum amount of loops per channel was 5, so for IT there will be two channels with cooling out of the four channels available. For OT if we split the amount of cooling loops with 5 we get an uneven number of 5 channels. This would also leave only 2 loops available for BTL services. The BTL needs roughly 20kW of power, as where Tracker needs roughly 100kW. If the BTL needs 20% of power what the Tracker needs it makes sense that it would also need 20% of the cooling that Tracker needs. Therefore, 2 loops out of 25 would not be enough as it would be only 8-9% of Trackers cooling. Due to this, one more OT channel with 5 cooling loops is introduced. Now out of 30 cooling loops available there are 7 free for BTL, which is roughly 20%.

In total per end there are now 6 OT channels with cooling and 8 OT channels without cooling, and 2 IT channels with cooling and 2 without cooling. Now it is possible to spread the services into the channels and see how full the channels are at the Section 2.

Table 3. OT Services distribution

Service channel	Name	OT Power cable PS modules	OT Power cable 2S modules	Total Power cables	MFB	Cooling pipe pairs	Dry gas injection pipes	Sniffing pipes	Environment sensors	Total area of services (cm2)	Channel fill
3	OT1	32	0	32	36	5	3	1	7	146.3	77%
4	OT2	33	36	69	72	0	3	1	7	137.3	72%
5	OT3	14	17	31	36	5	3	1	7	144.5	76%
6	OT4	33	36	69	72	0	3	1	7	137.3	72%
7	OT5	18	18	36	36	5	3	0	7	153.1	81%
8	OT6	31	36	67	72	0	3	0	6	133.3	70%
12	OT7	0	35	35	36	5	3	1	7	151.7	80%
13	OT8	32	36	68	72	0	3	1	7	135.5	71%
14	OT9	15	18	33	36	5	3	1	7	148.1	78%
15	OT10	32	35	67	72	0	3	1	7	133.7	70%
16	OT11	18	18	36	36	5	3	0	7	153.1	81%
17	OT12	33	36	69	72	0	3	0	6	136.8	72%

In the Table 3 for OT service distribution it is clear that the fill ratio is very close or above the 75% maximum allowed fill ratio in many places. It is not possible to lower this value by shuffling the services around, so a proposal for enlarging the smaller channel sections needs to be made.

Table 4. IT Services distribution

Service channel	Name	IT Power cables 2-chip	IT Power cables 4-chip modules	IT Power cables LpGBT	Total Power cables	MFB	Cooling pipe pairs	Dry gas injection pipes	Sniffing pipes	Environment sensors	Total area of services (cm2)	Channel fill
2	IT1	26	29	6	**61**	16	0	3	1	9	115.9	61%
9	IT2	26	29	6	**61**	16	0	3	2	9	116.2	61%
11	IT3	8	10	4	**22**	15	5	3	1	9	125.8	66%
18	IT4	8	10	4	**22**	15	5	3	1	9	125.8	66%

The IT service distribution shown in Table 4 seems good as it is.

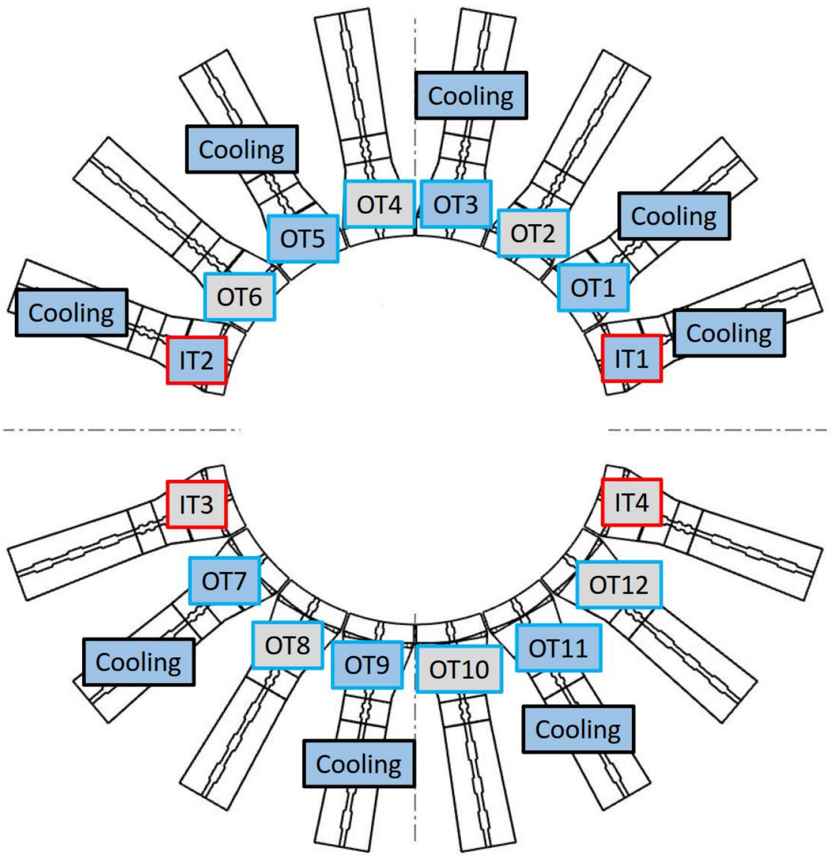


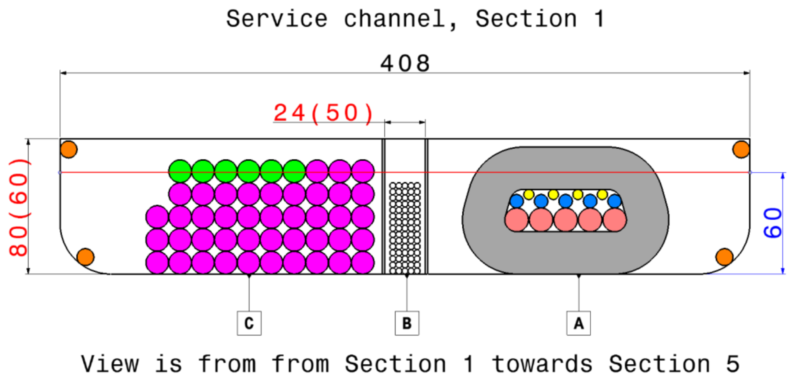
Figure 18. Cooling distribution of one +END.

In Fig. 18 it is possible to see visually which channels are used for the cooling in the +END of the tracker.

3.5 Channel enlargement proposal

To bring the fill factors of the channels down a proposal for enlarging the channel Section 2 needs to be made to bring up the cross section of the Section 2 at the same level with Section 3, 4 and 5. Moreover, also Section 1 should be enlarged to keep the cross sections of the Service channel constant through the whole channel. It is not possible to make the service channels wider than they already are, so an increase in height is needed. To make the cross sections constant in every section the heights of the Section 1 and 2 are proposed to be increased by 20mm.

Section 1



SECTION 1	A	B	C
Area (cm2)	136.0	19.2	136.0
Power cables (cm2)			86.2
MFB (cm2)		11.7	
Cooling (cm2)	91.3		
Total consumed area (cm2)	91.3	11.7	86.2
FILL RATIO	**59%**	**49%**	**63%**

Cables for OT	
Unused	
Optical fiber bundles	
Inlet cooling pipes	
Outlet cooling pipes	
Dry gas injection pipes	
Insulation	
Channel water pipes	

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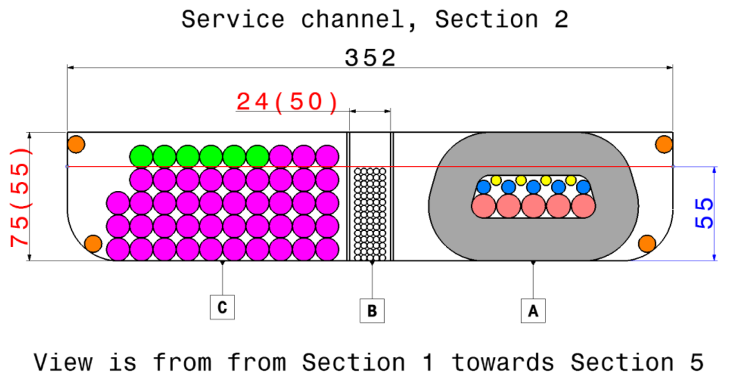
Figure 19. Enlarged Section 1 cross section

In Section 1 displayed in Fig. 19 the channel height is proposed to be increased from 60 mm to 80 mm. As we can see, without the increase it would also be impossible to fit 25 mm of Armaflex insulation with the cooling pipes without reorganizing the pipes.

Section 2



SECTION 2	A	B	C
Area (cm2)	119.9	18.0	119.9
Power cables (cm2)			86.2
MFB (cm2)		11.7	
Cooling (cm2)	91.3		
Total consumed area (cm2)	91.3	11.7	86.2
FILL RATIO	**67%**	**52%**	**72%**

Cables for OT	
Unused	
Optical fiber bundles	
Inlet cooling pipes	
Outlet cooling pipes	
Dry gas injection pipes	
Insulation	
Channel water pipes	

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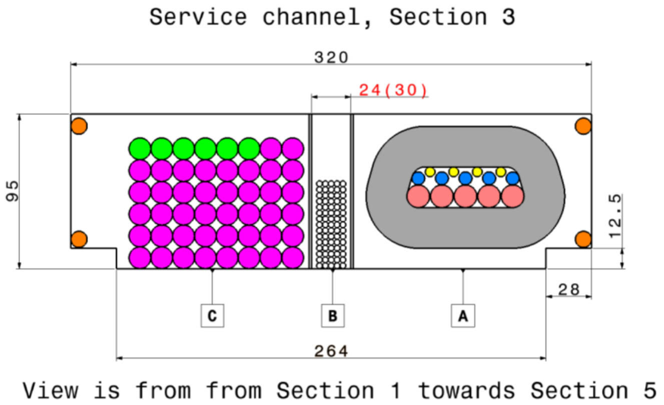
Figure 20. Enlarged Section 2 cross section

In Fig. 20 it is possible to see the Section 2 cross section. Here also a height increase proposed is from 55 mm to 75 mm.

Section 3



SECTION 3	A	B	C
Area (cm2)	135.7	22.8	135.7
Power cables (cm2)			86.2
MFB (cm2)		11.7	
Cooling (cm2)	91.3		
Total consumed area (cm2)	91.3	11.7	86.2
FILL RATIO	**59%**	**41%**	**64%**

Cables for OT	
Unused	
Optical fiber bundles	
Inlet cooling pipes	
Outlet cooling pipes	
Dry gas injection pipes	
Insulation	
Channel water pipes	

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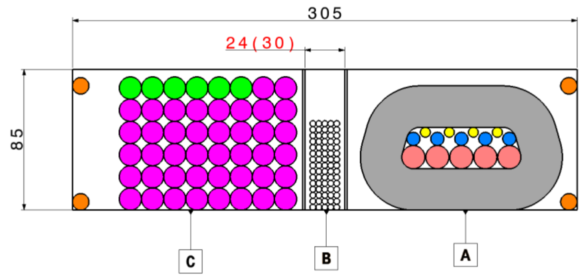
Figure 21. Section 3 cross section.

Fig 21. displays the service channel Section 3. No modifications needed.

Section 4

Service channel, Section 4



View is from from Section 1 towards Section 5

SECTION 4	A	B	C
Area (cm2)	118.2	20.4	118.2
Power cables (cm2)			86.2
MFB (cm2)		11.7	
Cooling (cm2)	91.3		
Total consumed area (cm2)	91.3	11.7	86.2
FILL RATIO	**68%**	**46%**	**73%**

Cables for OT	
Unused	
Optical fiber bundles	
Inlet cooling pipes	
Outlet cooling pipes	
Dry gas injection pipes	
Insulation	
Channel water pipes	

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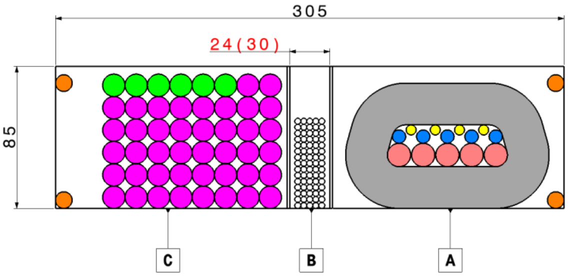
Figure 22. Section 4 cross section

Fig 22. displays the service channel Section 4. No modifications needed.

Section 5

Service channel, Section 5



View is from from Section 1 towards Section 5

SECTION 5	A	B	C
Area (cm2)	118.2	20.4	118.2
Power cables (cm2)			86.2
MFB (cm2)		11.7	
Cooling (cm2)	91.3		
Total consumed area (cm2)	91.3	11.7	86.2
FILL RATIO	**68%**	**46%**	**73%**

Cables for OT	
Unused	
Optical fiber bundles	
Inlet cooling pipes	
Outlet cooling pipes	
Dry gas injection pipes	
Insulation	
Channel water pipes	

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Figure 23. Section 5 cross section.

Fig 23. displays the service channel Section 5. No modifications needed.

3.5.1 3D model of services

After finding out the service distribution for the channels, 3D models of the channels and the services were made to visualize the cables, connections and pipes. As we have service channels that are full of power cables, and service channels that are split to half with power cables and cooling pipes, two general models were made to represent both cases. Time was also spent on analyzing the way of routing the services at the PP1 level to optimize space allocation of different services.

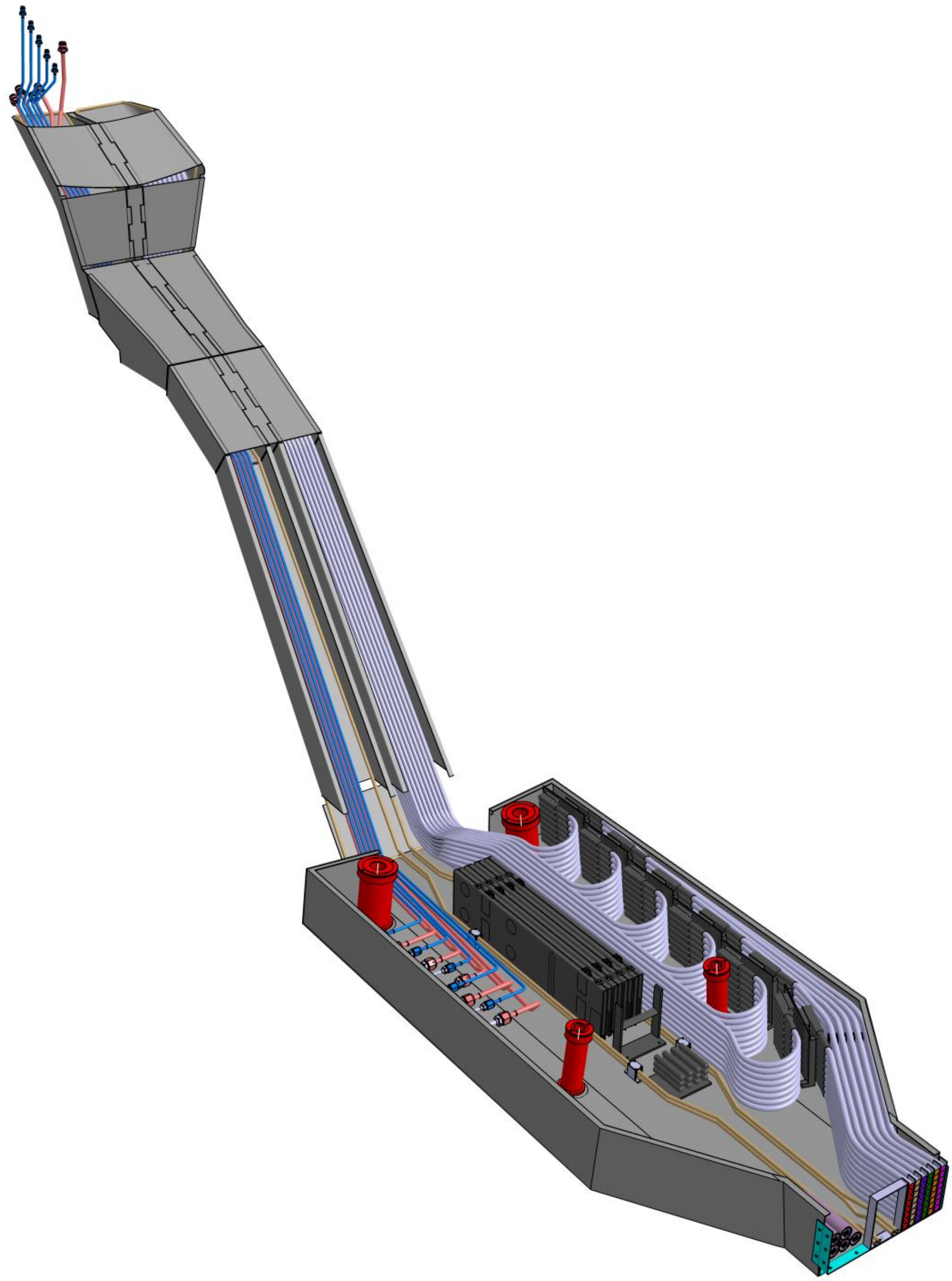

Figure 24. Service channel and PP1 with cooling pipes and power cables.

In Fig. 24 it is possible to see how the services look inside the PP1 and the service channel. In the figure the cover plates of Section 5 and the PP1 have been removed.

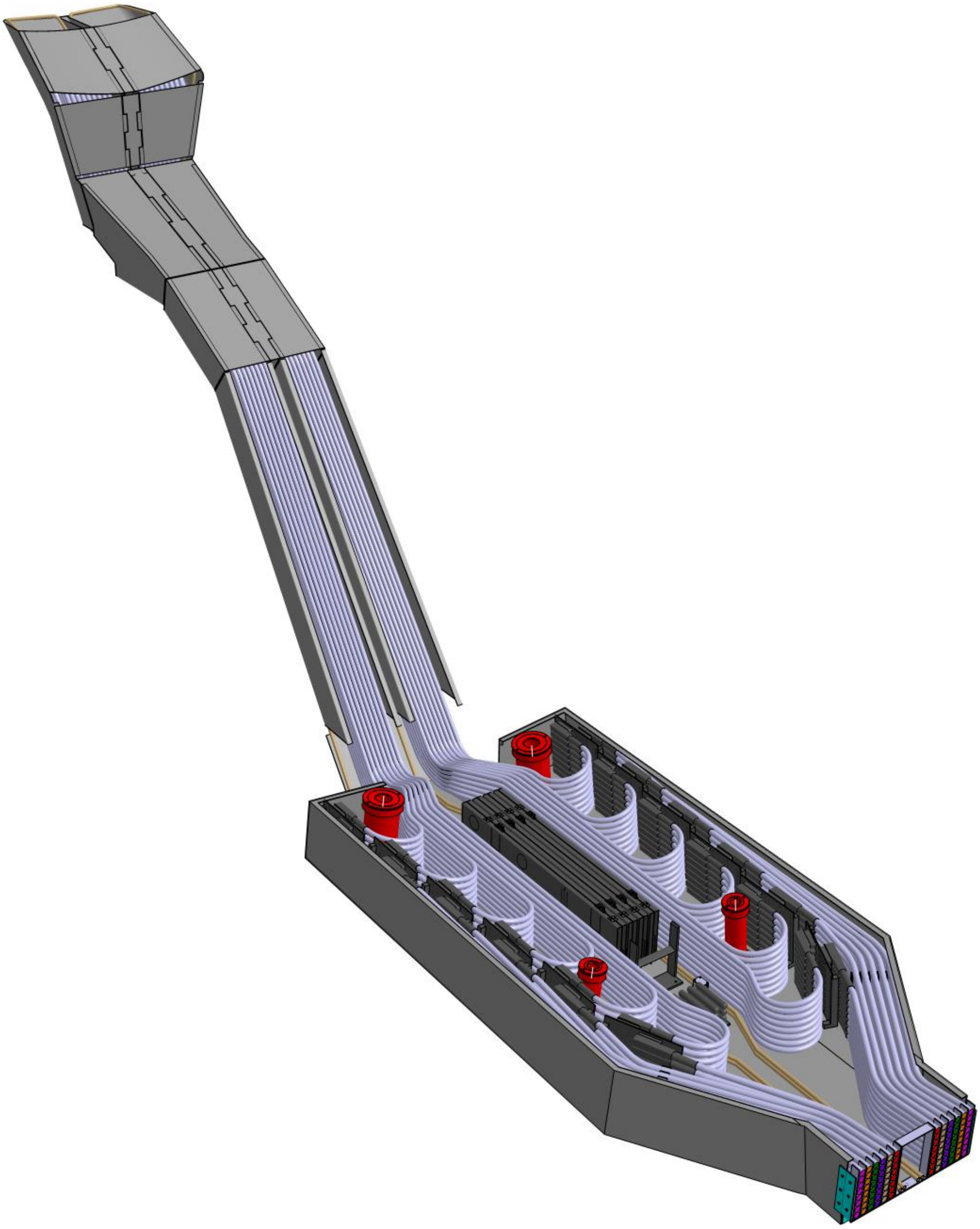

Figure 25. Service channel and PP1 with power cables only.

The Fig. 25 represents the case when the whole service channel and the PP1 are filled with power cables only. Here also some covers are hidden for visibility.

4 Phase 2 Service Channels Design

4.1 Approaching method

The service distribution for the channels has been found out, and the focus is now in the properties of the channels themselves. As described earlier in the thesis, there are problems with the current design of the channels. To find out possible solutions for overcoming the issues, some studies are required. All possible materials for the service channels need to be listed and studied to sort out which materials would be possible to use in the CMS environment. After possible channel materials are clear, the materials need to be applied in to the service channel design to see which materials have the most benefits. ANSYS simulations will be used to study the thermal properties of the channel.

4.2 What is required from the channels

The channels need to fill certain parameters to be usable inside the experiment. Firstly, surface temperatures of cooled channels need to stay above the dev-point of the surrounding air. Secondly, when a channel is only containing power cables, under full load the temperature inside the channel must stay low enough to not cause issues with the cables. Thirdly, the channels need to be mechanically robust enough not to deform under the mechanical stresses caused by the services.

4.3 Material choices

Not every material is suitable to be used inside the CMS, and some baseline considerations are listed below.

4.3.1 Radiation requirements

During the LHC runs the service channels will receive ionizing radiation. To ensure a safe work environment near the service channels when the LHC is not running, the materials used must possess suitable decay characteristics. This is due to the issue that after being bombarded with ionizing radiation from the LHC beam collisions, any material that will be decaying relatively strongly for a considerable amount of time will compromise the safety of the working environment. CERN has strict rules when working in an environment where radioactivity is present, and doses are limited to extremely safe levels. For example, using silver anywhere in the experiment would be a bad idea as it is considered to be strongly radioactive for a long time after receiving ionizing radiation. This affects, for example, which solder materials are usable inside the CMS.

4.3.2 Magnetic requirements

As the working principle of CMS is based on a 3.8 tesla magnetic field, the forces this magnetic field induces are strong. Therefore, the use of non-magnetic materials is preferred to avoid any unnecessary stresses and risks caused by the magnetic field. Non-magnetic materials like aluminum would be optimal from this point of view.

4.3.3 Thermal requirements

From a thermal environment point of view, well-conductive materials would be preferred for the service channels. As explained before, the issue with condensation inside the channel was caused by too low temperatures. This could possibly be avoided by using more conductive materials for the channels, while also making sure that the insulation design and geometry is already such that a proper contact with the channel and water loop is ensured and air pockets are eliminated. Materials like copper and brass would be strong options from the thermal point of view.

4.4 Suitable materials

Even though the current channels that are made out of stainless steel are not optimal, stainless steel would still be a considerable option for the new channels if the issues listed earlier can be prevented. Stainless steel is strong and durable, so it would be good from a mechanical point of view. With stainless steel it is possible to use relatively thin walls and still have a channel that does not deform easily.

Aluminum would be one alternative for stainless steel. Aluminum has thermal properties that are more suitable for our use scenario, but its mechanical properties are not ideal for this kind of sheet-metal channel. It must be also kept in mind that aluminum is more expensive than stainless steel.

If getting adequate channels with stainless steel and aluminum turns out to be difficult, materials like copper or brass can be also considered. Copper is a highly conductive material, and brass would be a cheaper alternative. Non-metallic materials like carbon fiber composites would be an interesting option to consider, but most likely it would not be cost effective to use such materials.

5 Service channel simulation

ANSYS Fluent simulations will be used for studying and improving the channel design and to help choose a cost efficient material for the channels. The simulations will be done in 2D, and the geometry of the channels will be simplified. A material table based on ANSYS Fluent library, ANSYS library and other sources is built for this study to keep the results comparable. The simulations will be focused on the Section 5 of the service channel.

The Section 5 will contain 5 cooling loops in sub-section A, 48 power cables in sub-section C, empty sub section B, solid Armaflex insulation attached to the walls of sub-section A and 2 water loops soldered to the walls of sub-section A and C.

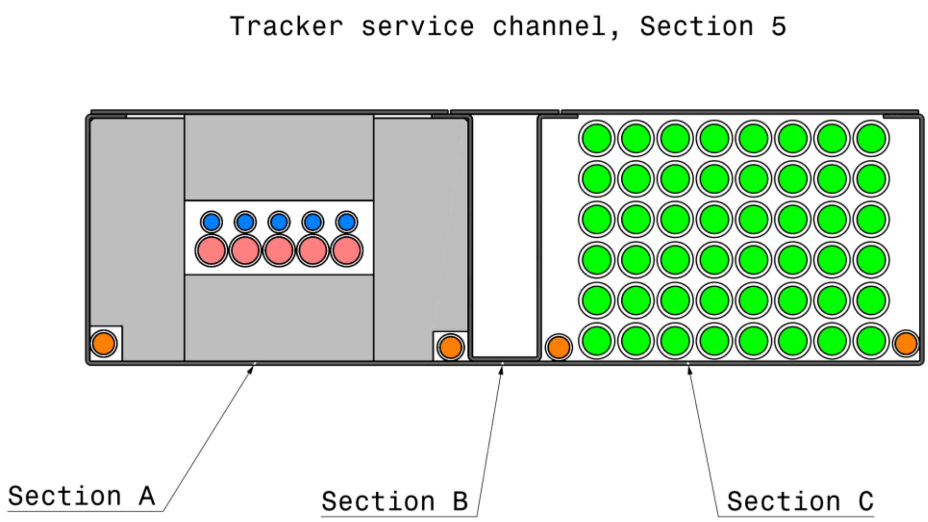

Figure 26. Section 5 baseline.

Six main scenarios are simulated, service channel with only cooling at full duty to simulate a worst-case scenario, a service channel with both cooling and power in full duty to compare the results with the worst-case scenario, both scenarios will be simulated with stainless steel and aluminum. If necessary other simulations can also be carried out if results from these simulations indicate that more studying should be done.

5.1 Simulation input

As a baseline input, the cooling will be run at -40 degrees Celsius, the service channel frame will have convection to 20-degree static air with a heat transfer co-efficiency of 5 W/m2-K on every side and the individual power cables have a heat generation of 9706 W/m3 per cable. The water loops will be defined as convection from copper pipe to 18 degrees Celsius water with a heat transfer co-efficiency of 7482 W/m2-K. The cooling temperature of -40 degrees Celsius is a worst case scenario estimate. The convection of the service channel frame is based on a pre-set estimated value for static air in ANSYS.

The heat generation for one cable was calculated in the following manner. One power cable for Tracker contains 12 low voltage links. The current in each link is 0.7A. The electric department has estimated that the power cable has a voltage drop of 0.1V per meter. From this it is possible to calculate that one cable has a power loss of 0.84 W/m. It is assumed that all lost power is turned into heat. In the simulation, the heat generation will be applied to the uniform cable core material, so the heat generation will be calculated for its volume. The diameter of the cable core is 10.5mm, therefore the end of the cable core has an area of 0.865 cm2. Heat generation is calculated for one meter of the cable, so the power loss of 0.84 W/m is divided with the area of the end of the cable core, resulting in a heat generation of 9706 W/m3 per one meter of cable. This input will be applied individually to each power cable.

The water loop input was calculated from the known values of the loop. The water loop will have a flow of 5 l/min, and the water temperature inside the loop is 18 degrees Celsius. The inner diameter of the water pipe is 8mm, and it has a wall thickness of 1mm. To find out the heat transfer co-efficiency from the water to the wall of the pipe following calculations were made.

Table 5. Material properties of water.

Parameter	Value	Unit	Temperature (Celsius)	Source
Kinematic viscosity (υ)	0.0000010533	m2/s	18	(8)
Dynamic viscosity (μ)	0.0010518	Pa*s	18	(8)
Dynamic viscosity (μ_s)	0.0010521	Pa*s	17.988	(8)
Thermal conductivity (k)	0.59803	W/m-K	18	(8)
Specific heat (C_p)	4180	J/kg-K	18	(8)
Density (ρ)	998.57	kg/m3	18	(8)

Values from Table 5 are used in the following calculations. Firstly, Reynolds number was calculated to find out if the flow is laminar or turbulent. If the Reynolds number is below 2320 the flow is laminar, and if the number is above 2320 the flow is turbulent [7]. For calculating the Reynolds-number the Eq. 1 was used.

$$Re_D = \frac{vD}{\upsilon} \tag{1}$$

Reynolds-number for this case is 12600, therefore it is safe to say that the flow is turbulent. Next, Prandtl number is calculated to determine which correlation equation for turbulent flow will be used to find out the heat transfer co-efficiency. Prandtl number is calculated with the Eq. 2. [6.]

$$Pr = \frac{\mu/\rho}{k/(C_p*\rho)} \tag{2}$$

Prandtl number calculated for this case is 7.352. Now that Prandtl number is found, it is possible to calculate Nusselt number. Nusselt number will be calculated with Sieder-Tate correlation for turbulent flow [21], because the correlation is valid for turbulent flows with Prandtl numbers between 0.7 and 16700 [8]. Eq. 3 shows the equation for calculating Nusselt number with Sieder-Tate correlation. In Sieder-Tate correlation μ means fluid viscosity at the bulk fluid temperature, and μ_s means fluid viscosity at the heat-transfer boundary surface temperature.

$$Nu_D = 0.027 * Re_D^{\frac{4}{5}} * Pr^{\frac{1}{3}} * \left(\frac{\mu}{\mu_s}\right)^{0.14} \tag{3}$$

Nusselt number calculated for this case is 100.089. The Nusselt number will be used to extract the heat transfer co-efficiency h from the Eq. 4. The D in Eq. 4 refers to the inner diameter of the water pipe. [8.]

$$Nu_D = \frac{h}{k/D} \tag{4}$$

$$h = \frac{k}{D} * Nu_D \tag{5}$$

Heat transfer co-efficiency (h) for the water loop calculated with Eq. 5 is 7482 W/m2. This parameter will be applied to the inner wall of the water pipe at 18 degrees Celsius.

5.2 Modeling methods

A simplified 2D cross section of the channel section 5 is made with Catia. The geometry is simplified in many ways from the original, since the starting point for the simulation is too complicated to obtain good results in reasonable time.

Firstly, all fillets and round shapes that are not necessary are eliminated. Making the model as sharp edged as possible makes the generation of mesh for simulation simpler and less time consuming.

Secondly, the channel frame is simplified as much as possible, and the covers and B-section are merged to one frame piece. This is done to eliminate small pieces that un-necessarily complicate the meshing.

Thirdly, the solders between the water pipes and the channel frame are simplified as much as possible. This concludes the simplifications made with CATIA. In Fig. 27 it is possible to see the resulting 2D model after all Catia simplifications.

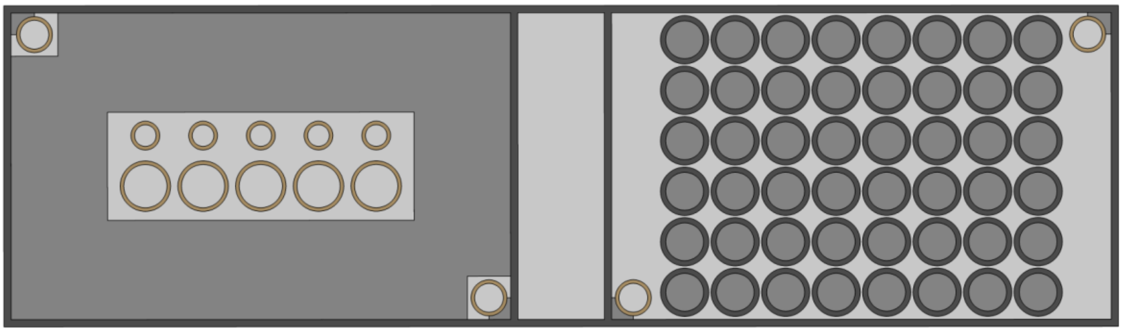

Figure 27. Channel geometry simplified in CATIA

Fourthly, since the cooling pipes are inside of an air volume that is being constantly flushed with dry gas at the same temperature as the cooling, therefore the pocket containing the cooling pipes will be left empty, and the boundary condition of -40 degrees Celsius will be applied to the inner boundary of the Armaflex insulation. The reason why this modification is going to be done in ANSYS is that if there is a need to look-into more in detail the space inside the insulation, the model does not need to be remodeled completely. Fig. 28 shows the resulting geometry in ANSYS.

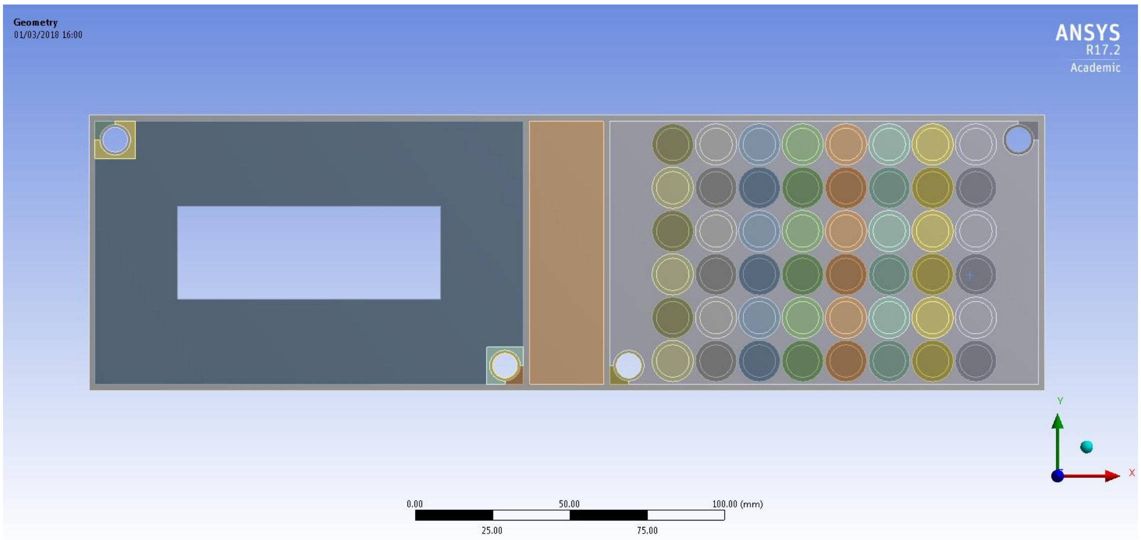

Figure 28. Simplified Section 5 for ANSYS

After geometry was created with Catia it was exported to ANSYS via ANSYS spaceclaim. In space the topology method was selected to be shared with all parts of the model, this is essential to keep the model simple, as otherwise every contact between all objects need to be defined separately. The mechanical model used in the simulation is meshed with the ANSYS mechanical workbench. The two most important factors to take into account when meshing for Fluent analyses, are to make sure that all objects are at least 4 elements thick to ensure good simulation results, and if possible, the mesh should be kept as hard-quad based mesh whenever possible. Hard-quad based mesh shown in Fig. 29. Since the geometry contains many round objects like pipes, keeping the mesh hard-quad based is difficult, but possible to some degree. Difficult locations for meshing shown in Fig. 30. Since the main concern of the simulation is the frame of the service channel, an element size of 0.5mm was chosen as baseline for all geometry to ensure that the channel wall has a consistent thickness of 4 elements. To achieve a good overall mesh otherwise, all meshes for pipes and cables were defined by firstly edge splitting the shape to appropriate size, and then using face meshing to split the edge-split objects to ensure a thickness of 4 elements through all thin objects.

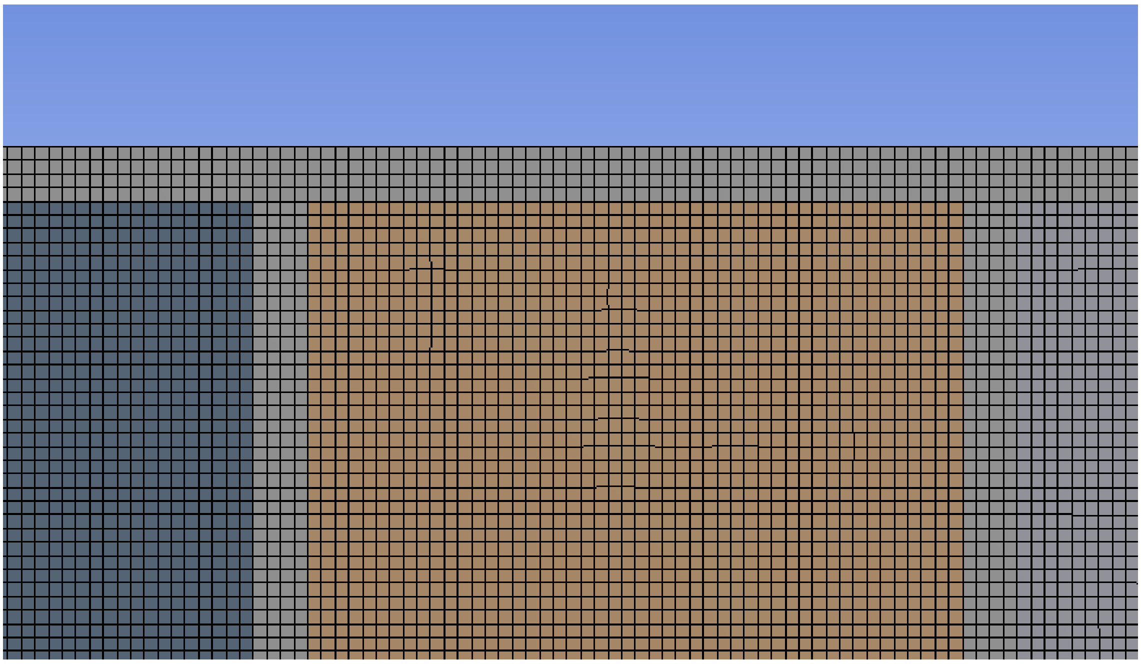

Figure 29. Example of hard-quad based mesh.

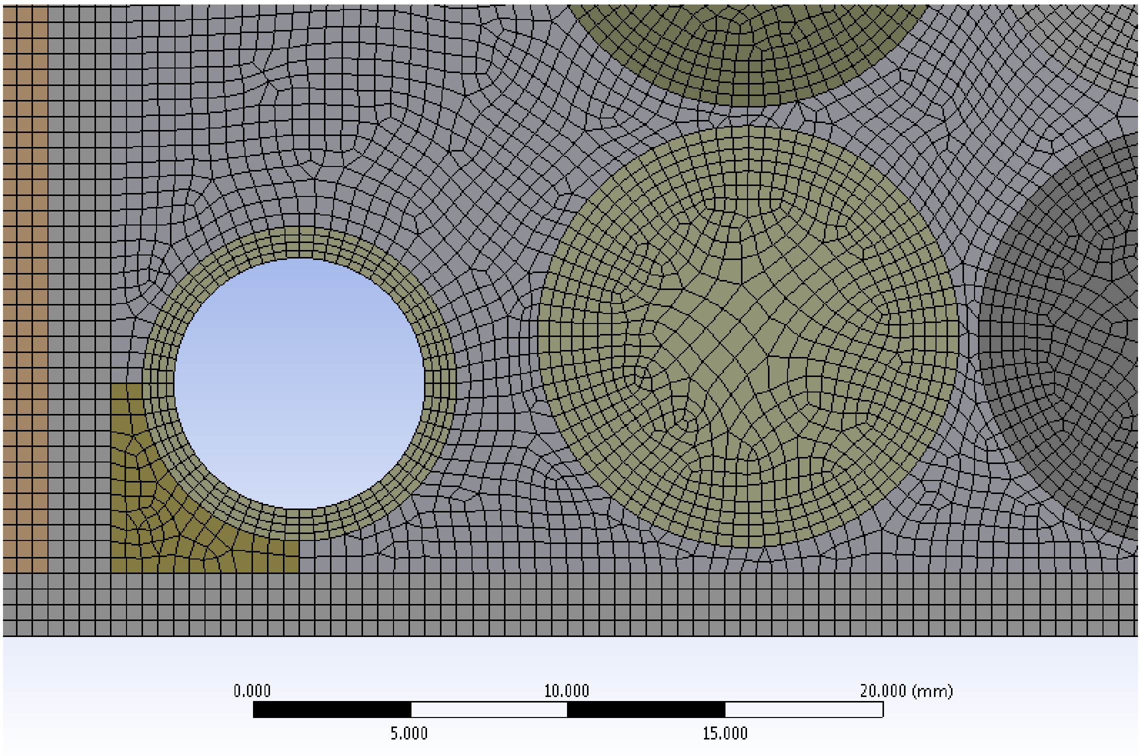

Figure 30. Detail of meshing around cables and pipes.

5.3 Material parameters

The material properties for used materials were extracted from different sources. The preference was to use the existing material library of ANSYS and Fluent, but as Armaflex Class 0 is not a common material, its properties were extracted from Armacell datasheets. Since modelling the individual wires of each power cable would be time consuming and would significantly complicate the simulation, an average based “cable core” material was calculated for the volume inside the cables insulation. This material was calculated by taking all items inside the cable, calculating how many percent of the total area each item takes, and then averaging the density, conductivity and specific heat based on the split of materials. Since the focus on the simulation is the thermal performance of the service channel and not the mechanical stresses, most materials were given constant non-temperature dependent properties. However, to take natural convection into account in the simulations, air density was specified to follow the Fluent in-built Ideal Gas Law.

Table 6. Table of materials used in the simulation.

Material	Density (kg/m3)	Isotropic Thermal Conductivity (W/m K)	Specific Heat (J/kg*K) Cp	Source
Air	Ideal Gas Law	0.0242	1006.43	Fluent
Aluminum, General	2719	202.4	871	Fluent
Armaflex, Class 0	50	0.033	1500	(9, 10)
Brass, General	8600	111	162	ANSYS
CO2, Liquid	773	0.087	5000	Fluent
Copper, General	8978	387.6	381	Fluent
Cable core	1065	57	1543	Calculated
Polyethylene	930	0.4	2300	ANSYS
Solder, General	8000	48	167	ANSYS
Stainless steel, General	8027	16.26	502	ANSYS
Water, General	998.2	0.6	4182	Fluent

Table 6 displays the full material list used for the simulation.

5.4 Fluent parameters

The simulations in Fluent are run as Transient State simulations. A pressure-based solver is used for the simulations, as in the simulations there will only be low-velocity flows caused by natural convection [12]. The density-based solver would be ideal for high-velocity compressible flows, for example for studying combustion cycles inside an engine [12]. Boussinesq approximation is used for calculating the natural convection model [13]. Gravitational constant of 9.81 m/s2 is defined for the model to initiate realistic flows caused by natural convection.

6 Simulation result

6.1 Targets

The targeted frame temperature on the outside of the frame is above 13 degrees Celsius, as anything below that will cause condensation on the surface of the channel. Since the

Phase 2 channel will contain two cooling loops instead of one, it turned out that even with stainless steel it would be possible to keep the channel temperature above the dew-point. Since the simulations were run as transient simulations, it was also found out that it would take roughly an hour for the channel environment to stabilize after cooling is turned on. When the power was turned on, it takes nearly 7 hours of time for the channel to stabilize thermally.

6.1.1 Scenario 1, Stainless steel frame with cooling only

Looking into more detail in the channels that had only cooling switched on, in Fig. 31 it can be seen, that when there are two cooling loops with 2mm thick stainless steel the frame, temperature range in the frame is between 14.02 degrees Celsius and 18.67 degrees Celsius.

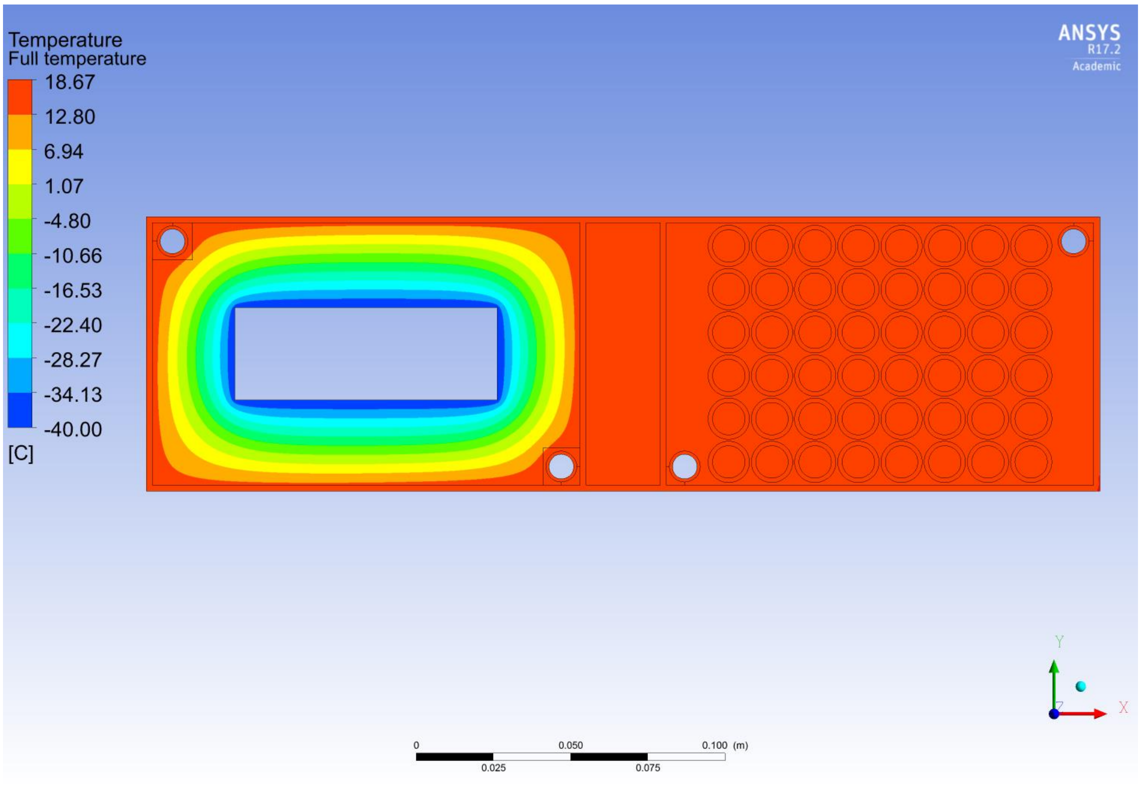

Figure 31. Overall temperature gradient.

On the frame a minimum temperature of 14.20 degrees Celsius can be observed in Fig 32. This is barely above the required temperature to overcome the condensation issue.

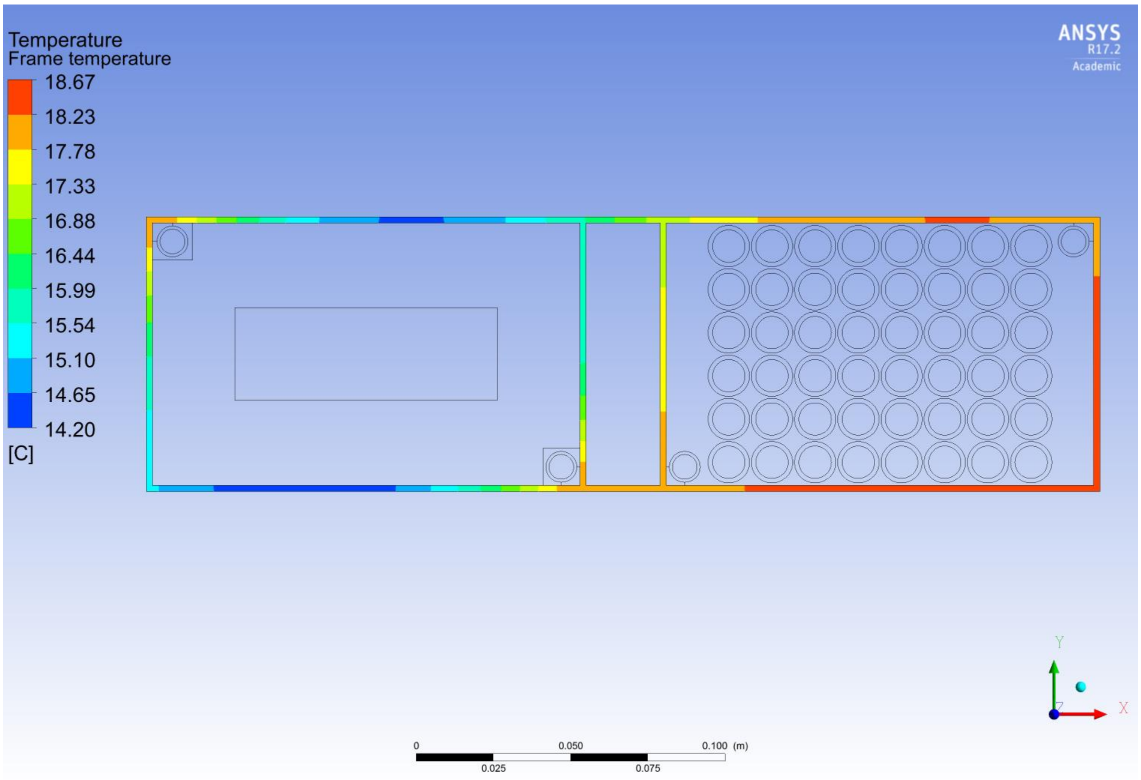

Figure 32. Frame temperature gradient.

In Fig. 33, on the water pipes it can be seen, that on the cooling side the water is being cooled, and on the power side the water is being heated. It is interesting to compare the numbers with the aluminum frame later-on.

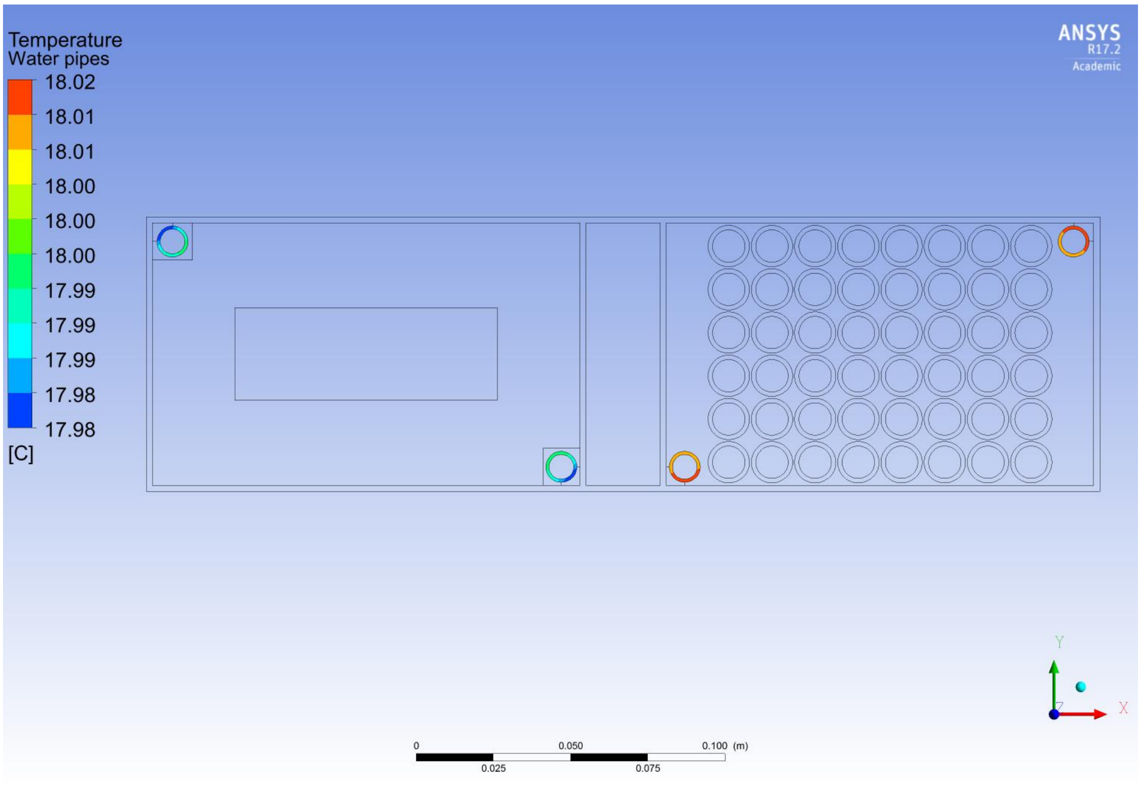

Figure 33. Water pipes temperature gradient.

6.1.2 Scenario 2, Aluminum frame with cooling only

With a 2 mm thick aluminum frame the overall temperature gradient looks very similar to the stainless steel. Fig. 34 displays the overview of temperatures.

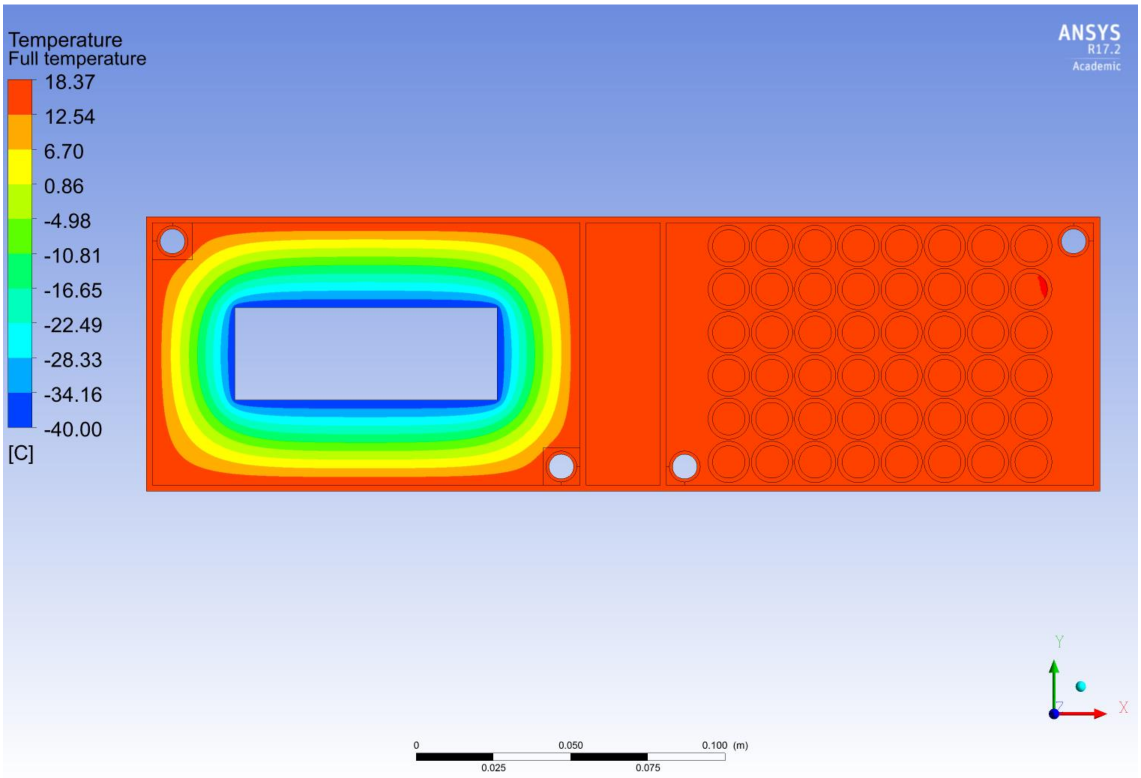

Figure 34. Overall temperature gradient.

However, the temperatures of the frame are considerably higher in comparison to the stainless steel. In Fig. 35 it can be seen, that the whole frame is above the temperature of the water circulation.

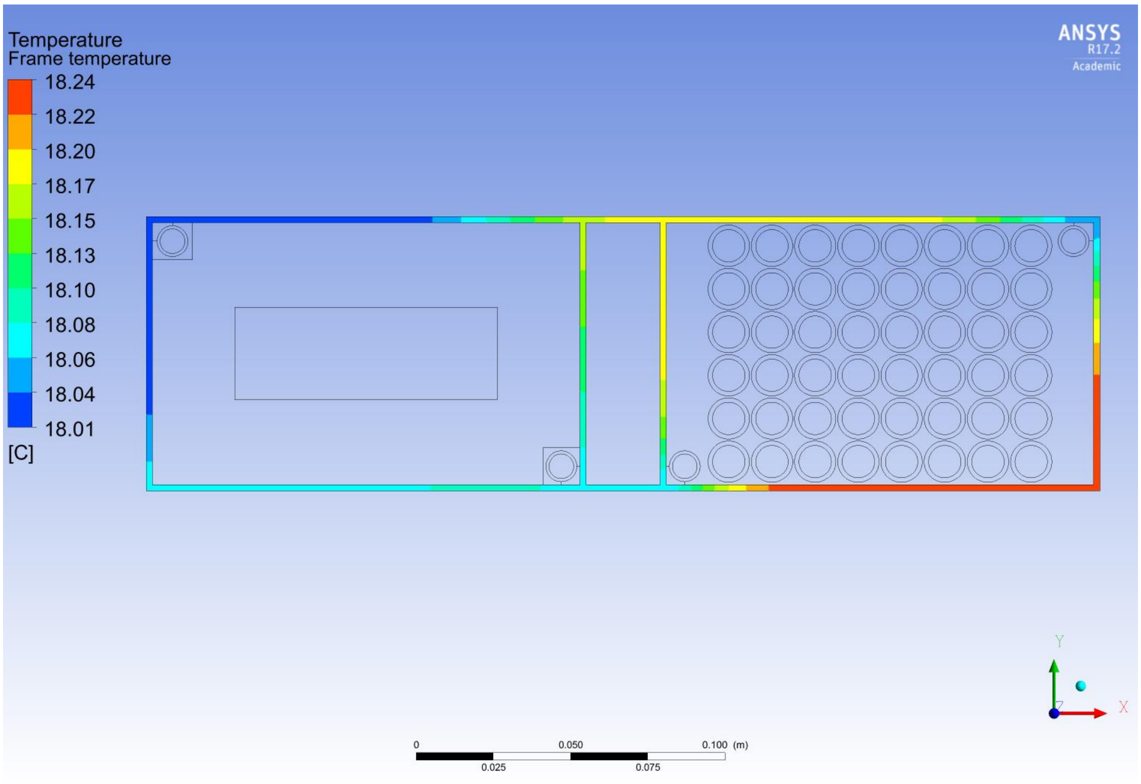

Figure 35. Aluminum frame temperature gradient.

When observing the temperature of the water pipes in Fig 36, it can be seen, that all of them are above the temperature of the water circulation. This is a clear indication of the aluminum being able to transfer heat so effectively, that the surrounding air starts to heat the water inside the water loops even when cooling is run at full power.

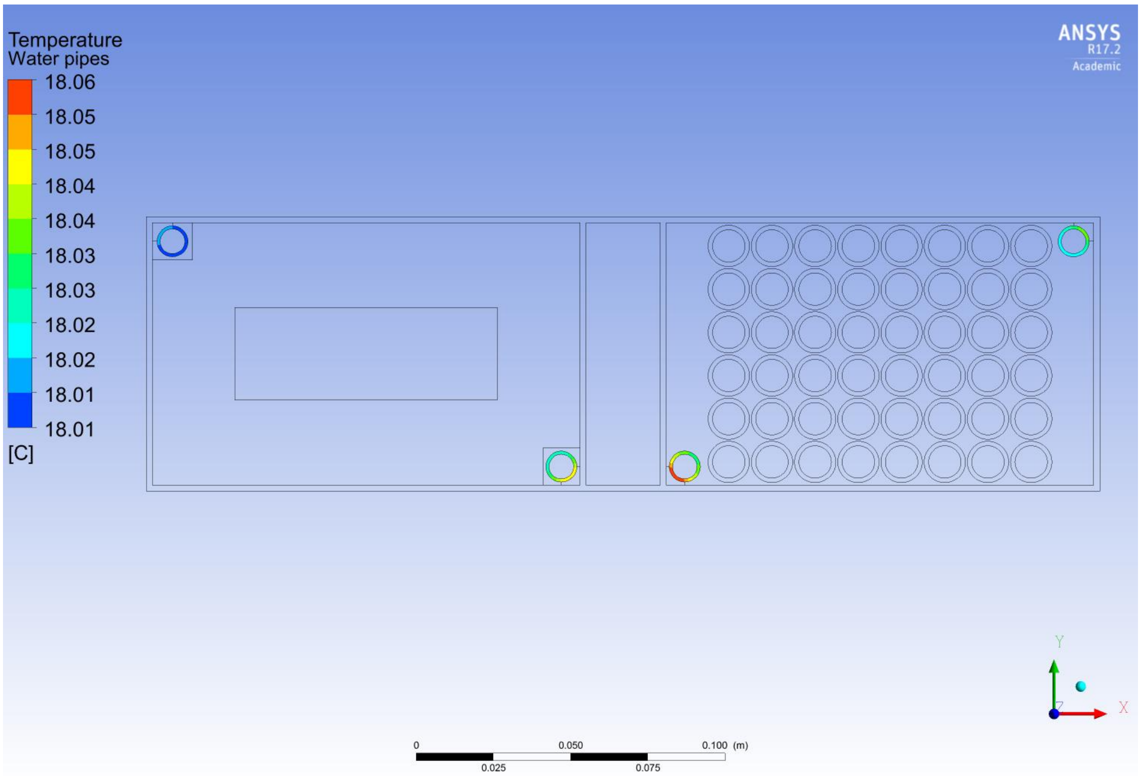

Figure 36. Aluminum frame with only cooling.

6.1.3 Scenario 3, Stainless steel frame with cooling and power

When the power was also switched on, a noticeable increase of maximum temperatures can be observed with stainless steel. The highest temperature of 46.8 degrees Celsius is logically found in the middle of the cables. Fig. 37 displays the overview.

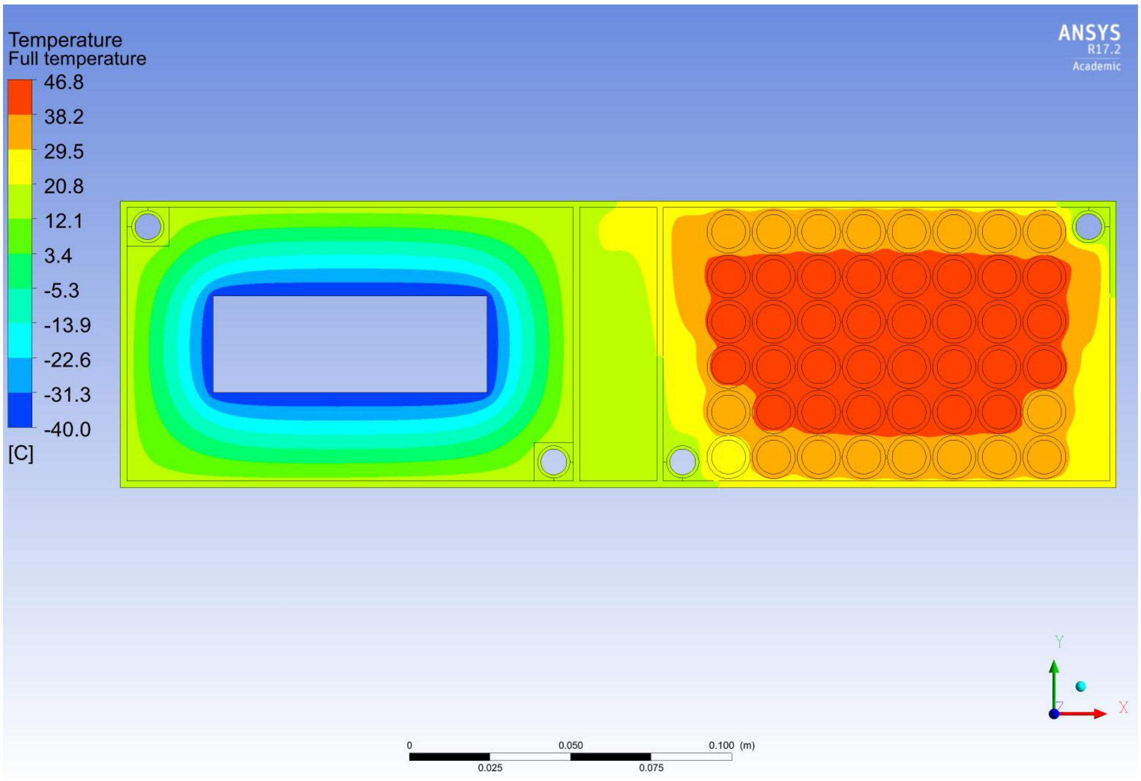

Figure 37. Overall temperature gradient.

On the frame in Fig. 38, a temperature-range from 14.2 degrees Celsius to 27.6 degrees Celsius can now be observed. It is good to note that the cold portion of the channel did not change when power is switched on with stainless-steel.

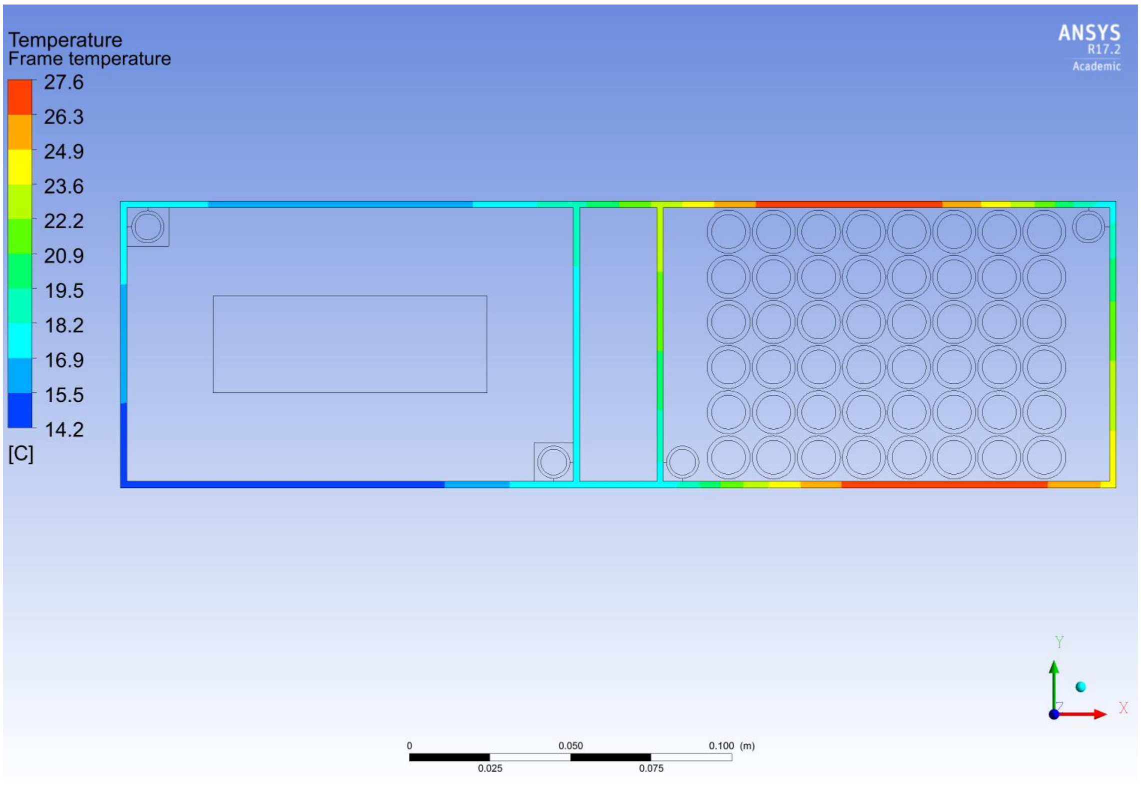

Figure 38. Frame temperature gradient.

In Fig. 39 it is possible to observe the cable temperatures. The cable temperatures vary from 25.9 degrees Celsius to 46.8 degrees Celsius. The limit temperature for the cables is approximately 60 degrees Celsius [21].

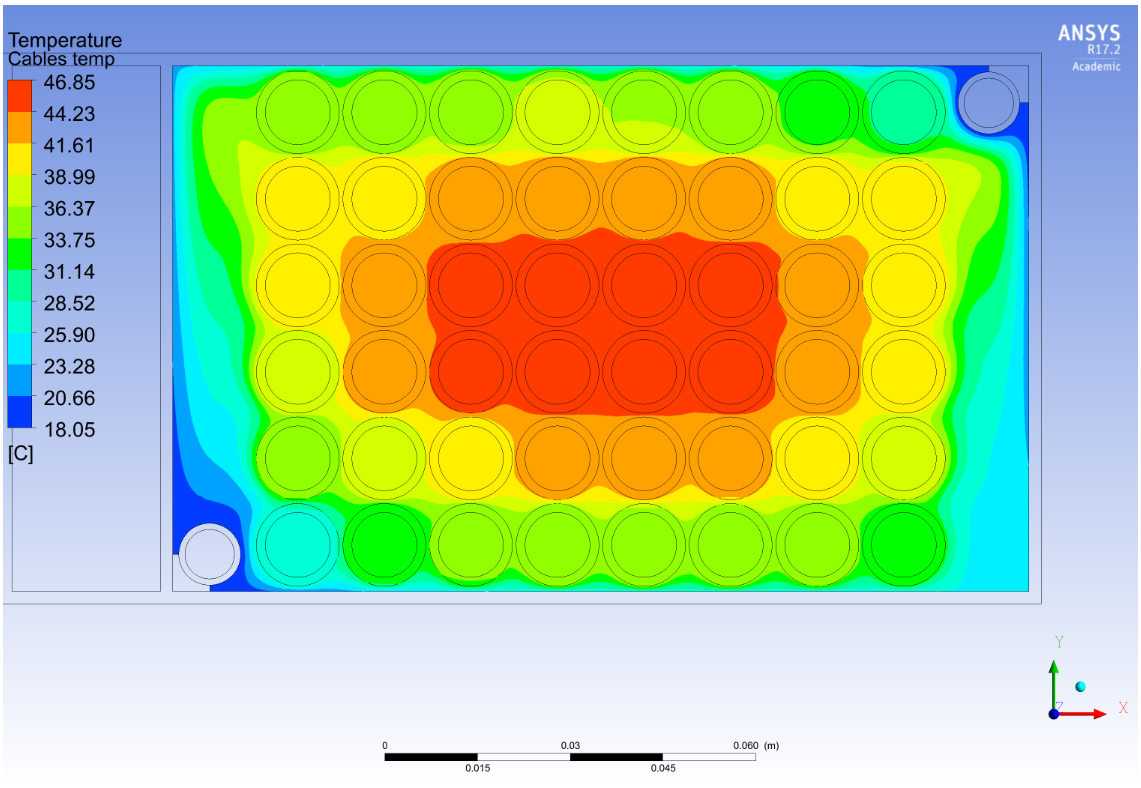

Figure 39. Temperature gradient of cables.

In Fig. 40, on the water pipes the temperatures vary from 18.11 degrees Celsius to 17.98 degrees Celsius. This indicates that on the cable side, the water is being heated and on the cooling side the water is being cooled down.

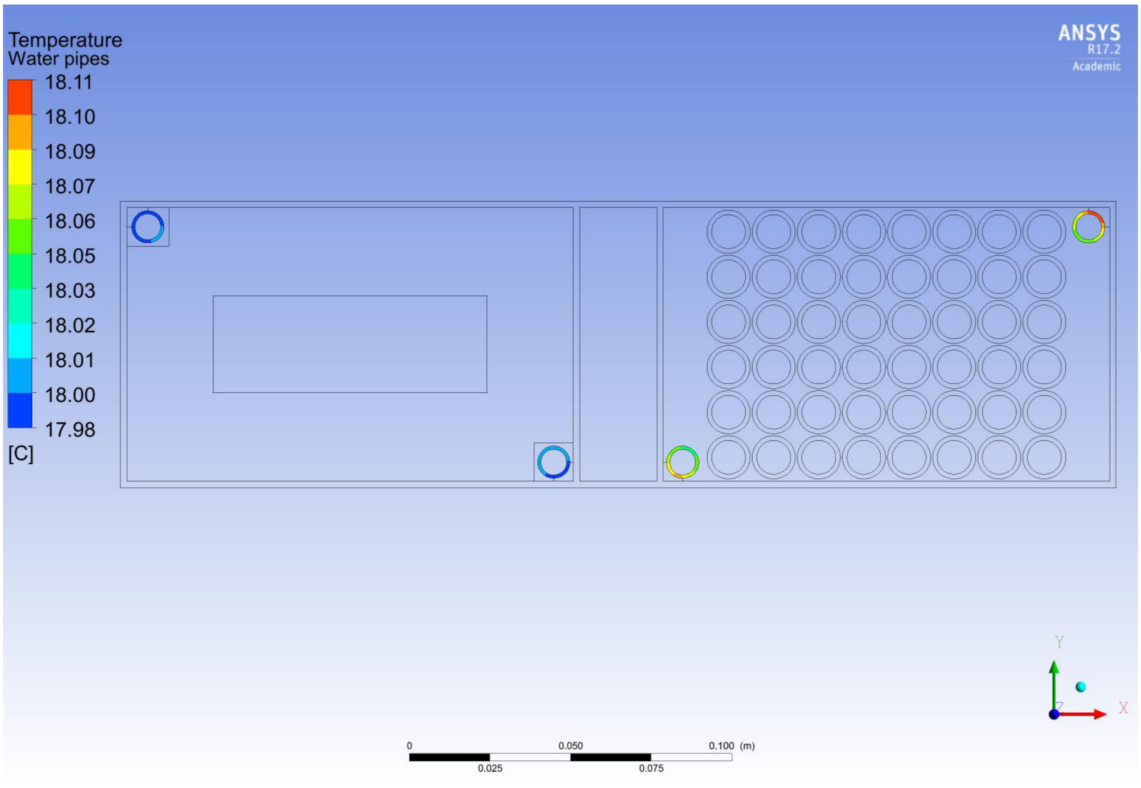

Figure 40. Stainless steel frame with cooling, power and two water loops active.

6.1.4 Scenario 4, Aluminum frame with cooling and power

Looking at the temperatures in Fig. 41 with aluminum when cooling and power are both switched on reveals that the aluminum frame affects the maximum temperature of the cables considerably. A drop of 5 degrees Celsius can be seen in comparison to Scenario 3

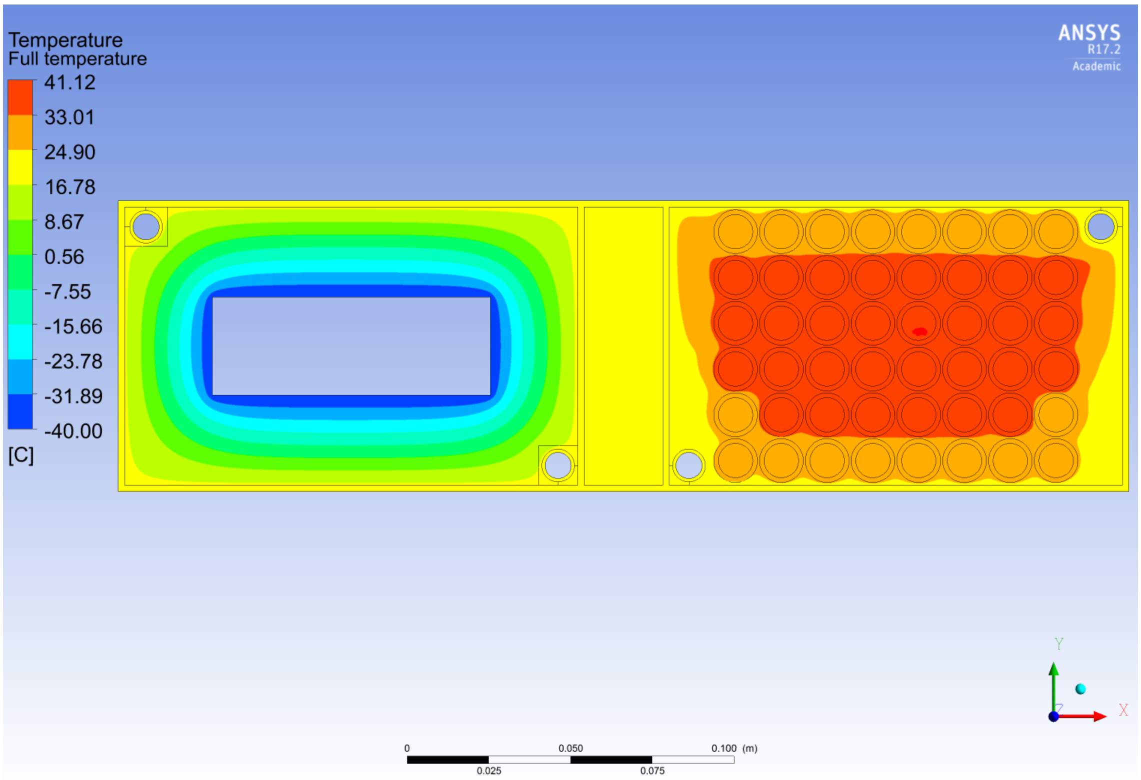

Figure 41. Overall temperature gradient.

In Fig. 42 with aluminum, the frame temperatures are also considerably lower than with stainless steel.

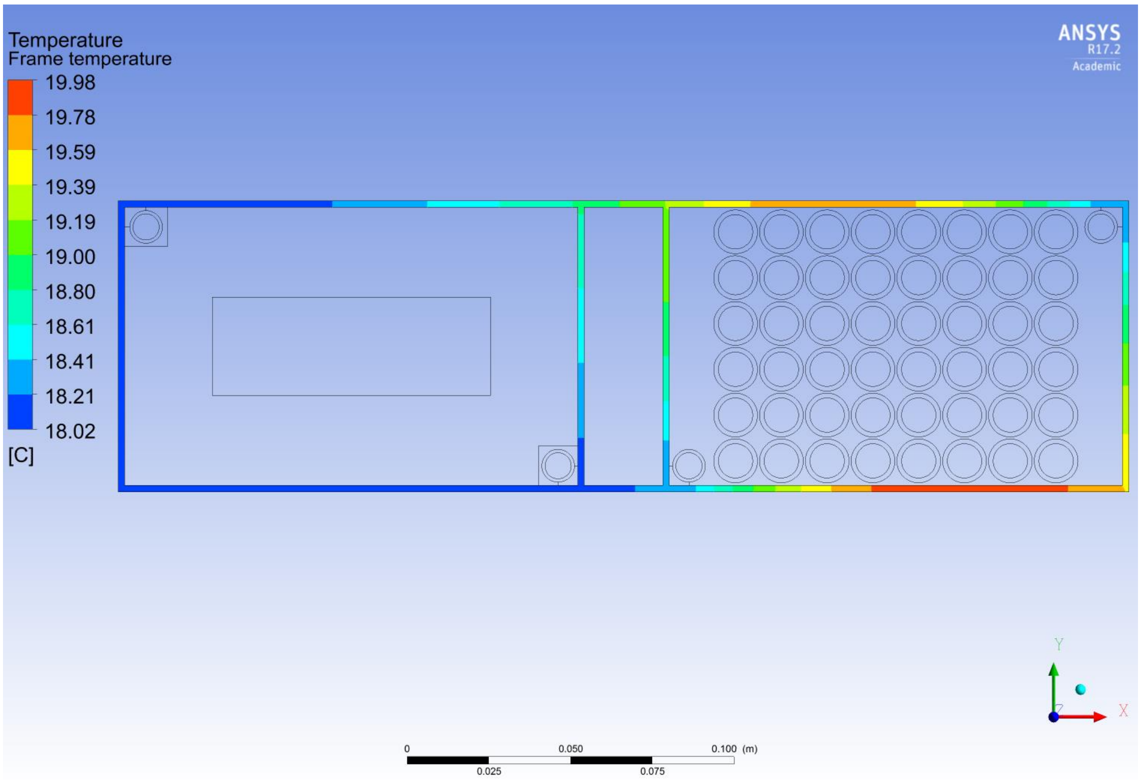

Figure 42. Frame temperature gradient.

In Fig. 43 it is possible to observe that the maximum temperature of the cables drops by five degrees with aluminum frame.

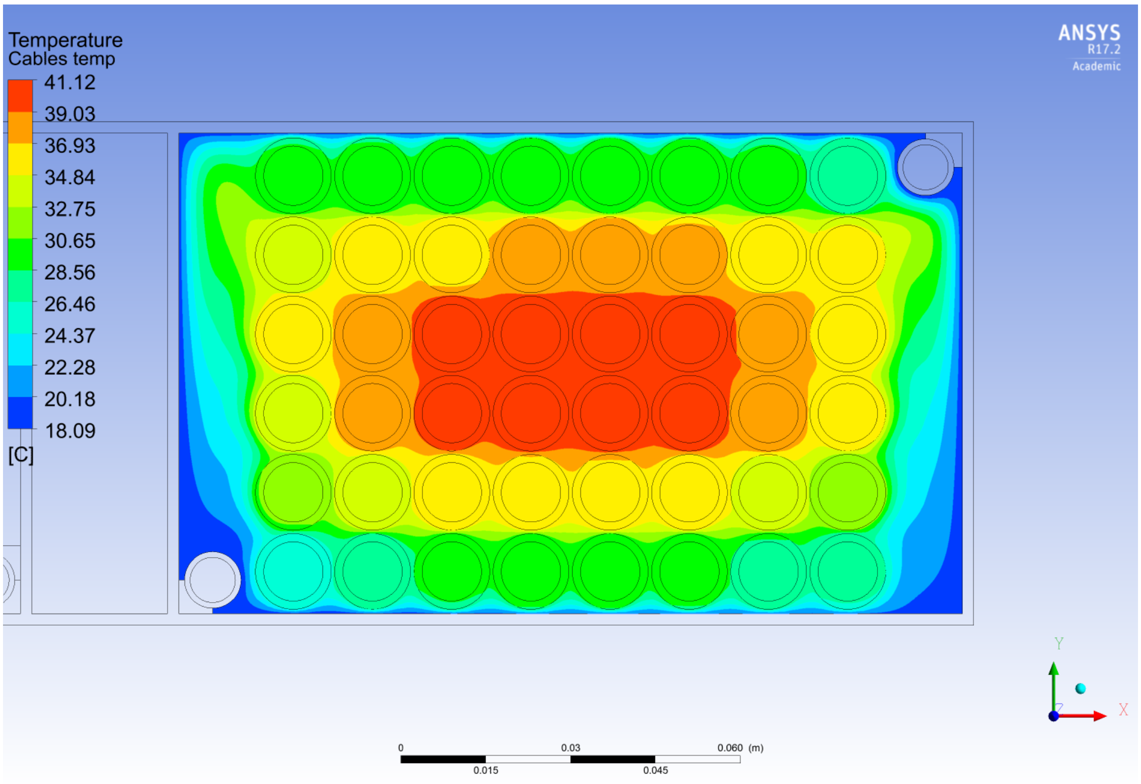

Figure 43. Cables temperature gradient.

Unlike with stainless steel, with aluminum all the water pipes are above the water temperature, meaning that the water is receiving heat even in the cooling side. This can be seen in Fig 44.

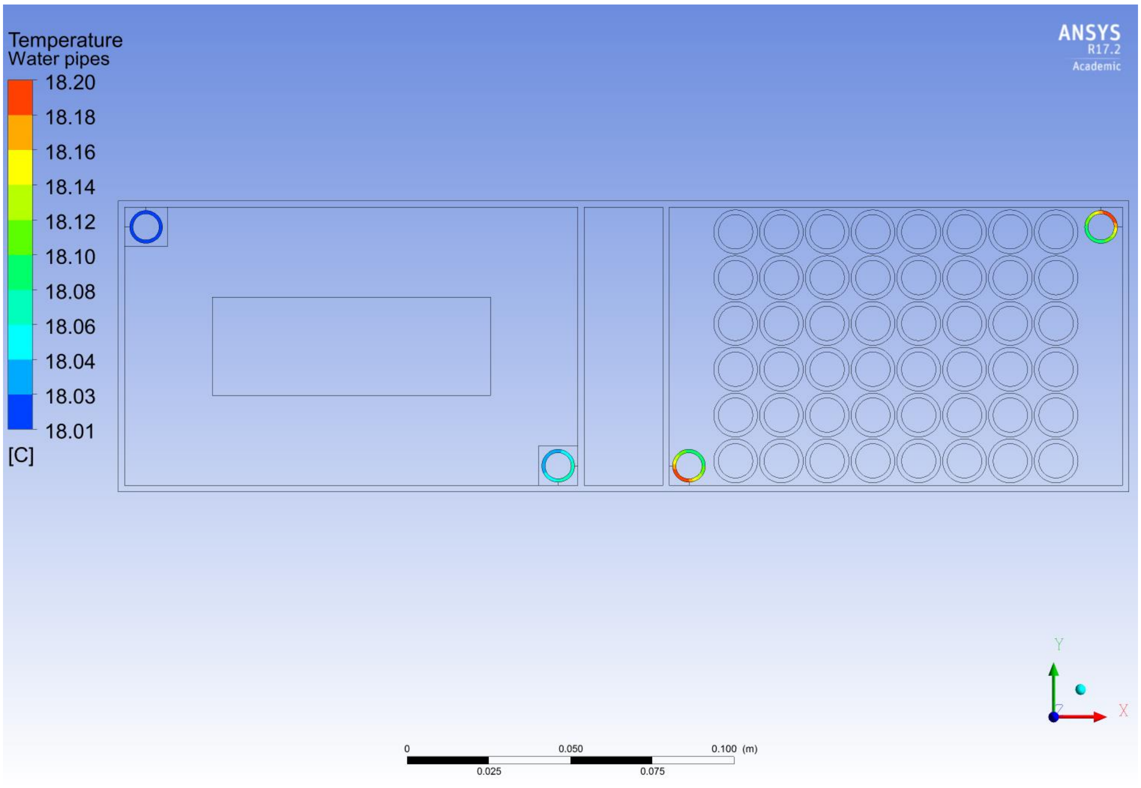

Figure 44. Pipes temperature gradient.

6.1.5 Velocity vectors

Also the velocity vectors of natural convection can be extracted from the simulation. These vectors were extracted from the Scenario 3 to see if fluid behavior looks natural and logical.

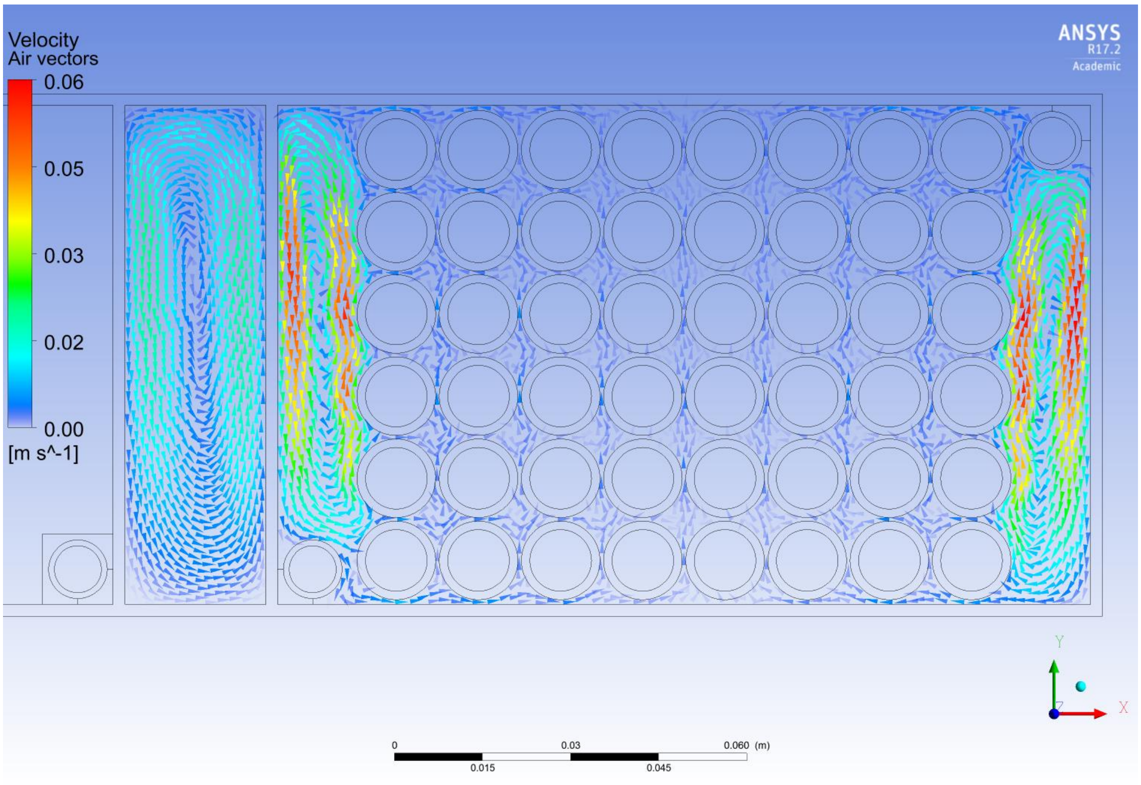

Figure 45. Velocity caused by natural convection.

Judging by the vector directions and velocities, the behavior looks correct. In Fig. 45 can be seen that the air in the warmer region is rising up, and after reaching the cooler regions, the air starts to sink, causing a natural looking swirl of the fluid. Also, it can be seen, that between the cables there are also streams of air rising up to the top of the frame, and then flowing towards the edges of the sub section where the cooler volume is found.

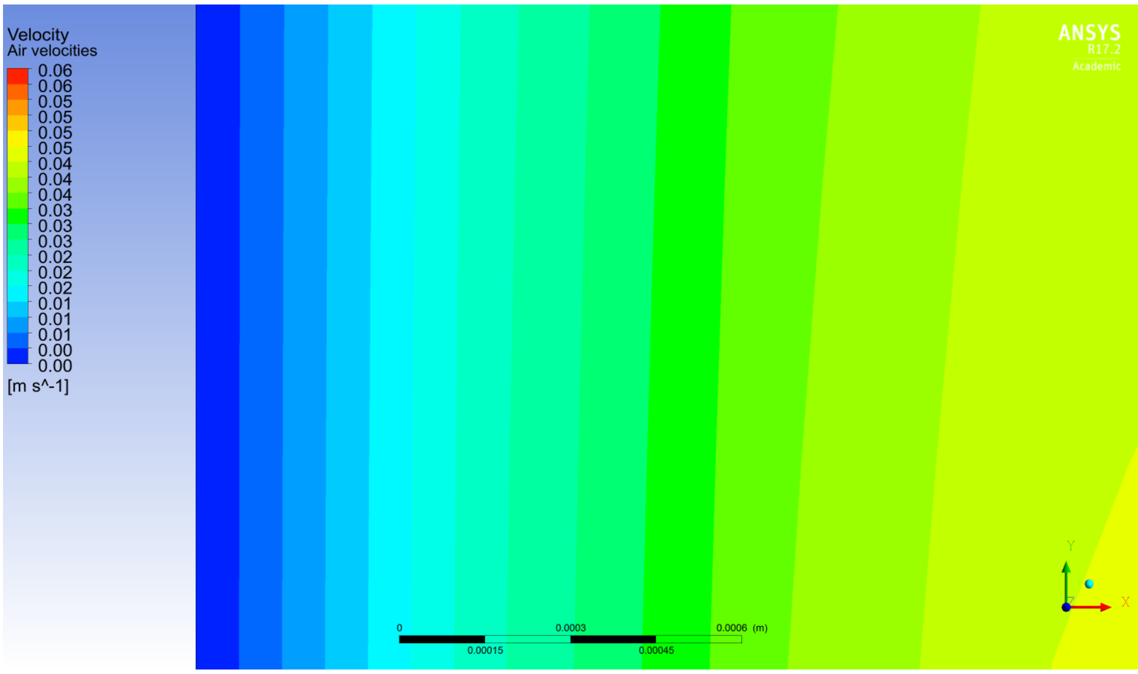

Figure 46. Air velocities near solid surfaces.

Since the laws of fluid dynamics define that at the surface of a solid object the fluid is always stationary in relation to the wall [6], it was also confirmed that the simulations are respecting this law. In Fig. 46 we can clearly see that this is true in the simulations.

7 Additional simulations

The simulations before were run with convection to surrounding 20 degrees Celsius air on every surface of the channel. This might not represent a realistic case as the sides of the channels will be facing other channels, and the bottom of the channel will be against the VAC-tank with small air-gap in between. Due to this, it was decided that two more simulations are run without the convection on the surfaces of the box. This does not represent a real life situation, because in reality the channel is not inside a void of nothing, but it gives a clue on how the channel would behave if it is not affected by anything outside the channel. These two simulations will be run with stainless steel and aluminum with both power and cooling switched on.

7.1 Results of additional simulations

7.1.1 Scenario 5, stainless steel frame without convection

The results of this scenario are comparable to the Scenario 3, as Scenario 3 represents the same case as this scenario, but with convection to surrounding air. The overview is displayed in Fig. 47.

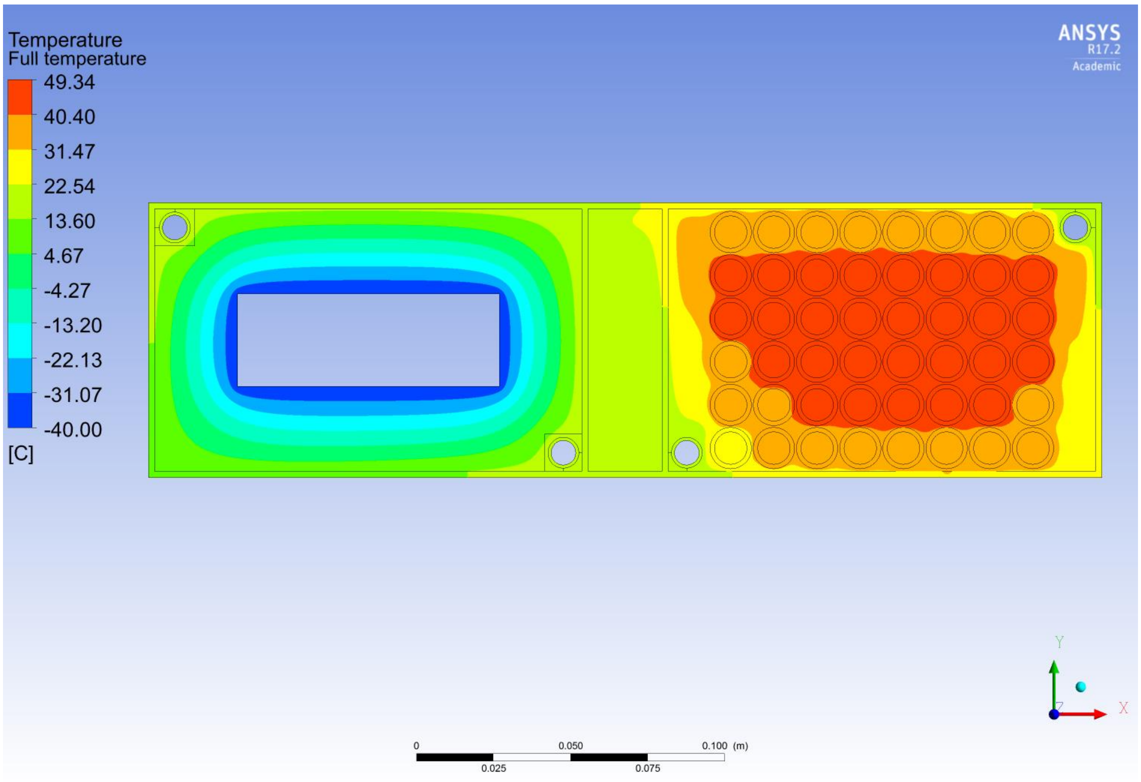

Figure 47. Full temperature gradient.

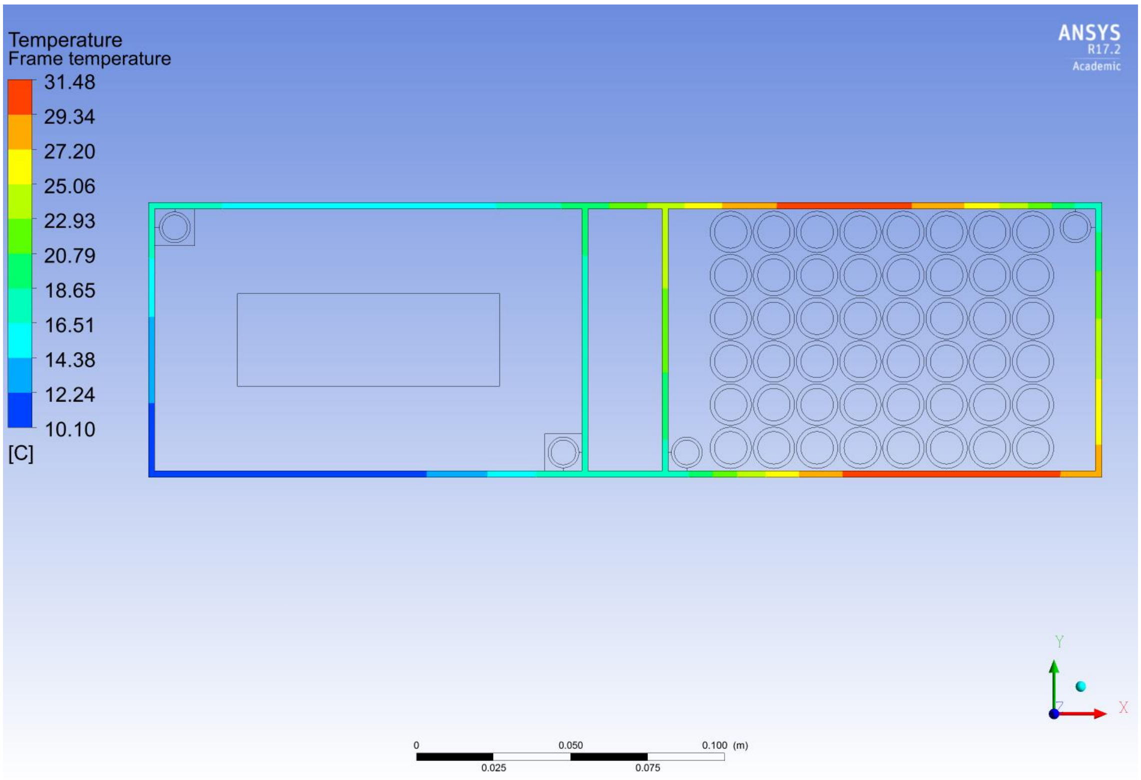

Figure 48. Frame temperature gradient.

Without convection to surrounding air, the frame temperatures drop significantly. This can be seen when comparing the Fig. 48 to Fig. 38. This indicates that there is a possibility that with stainless steel, the temperatures of the frame drop low enough to cause condensation issues if the surrounding air is slowly cooled down over time. Also the maximum temperatures on the frame are approximately 4 degrees higher than in the Scenario 3.

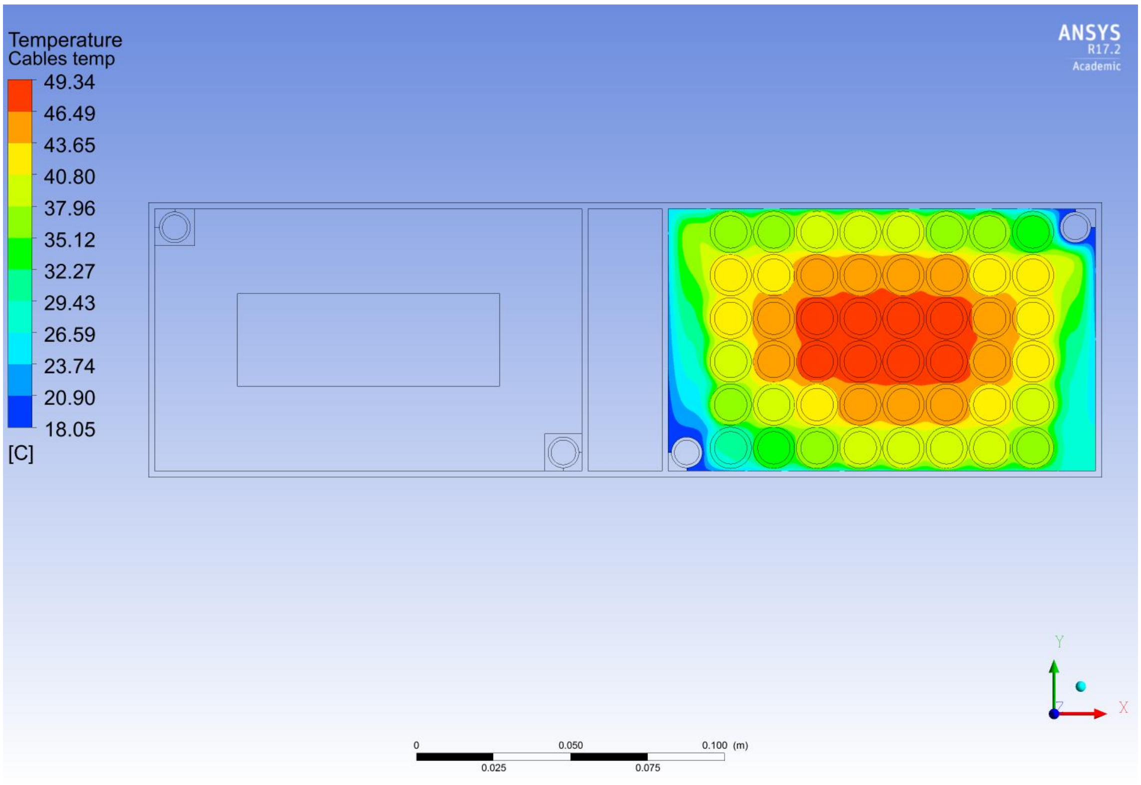

Figure 49. Temperature gradient of sub-section C.

In Fig. 49 maximum cable temperature is 49.3 degrees Celsius. This is approximately 4 degrees higher than in Scenario 3.

7.1.2 Scenario 6, aluminum frame without convection

The results of this Scenario are comparable to Scenario 4.

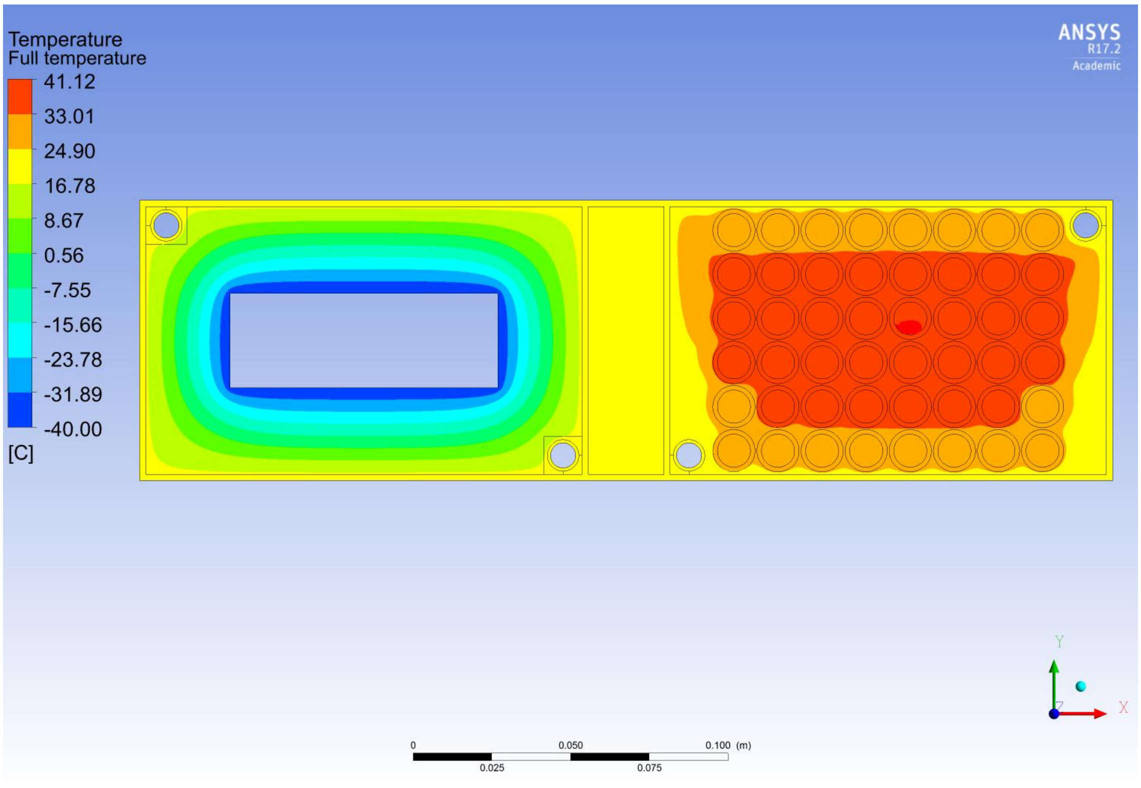

Figure 50. Full temperature gradient.

The results are almost identical with the Scenario 4. Almost no difference can be seen with Fig. 50 and Fig. 41 for the Scenario 4.

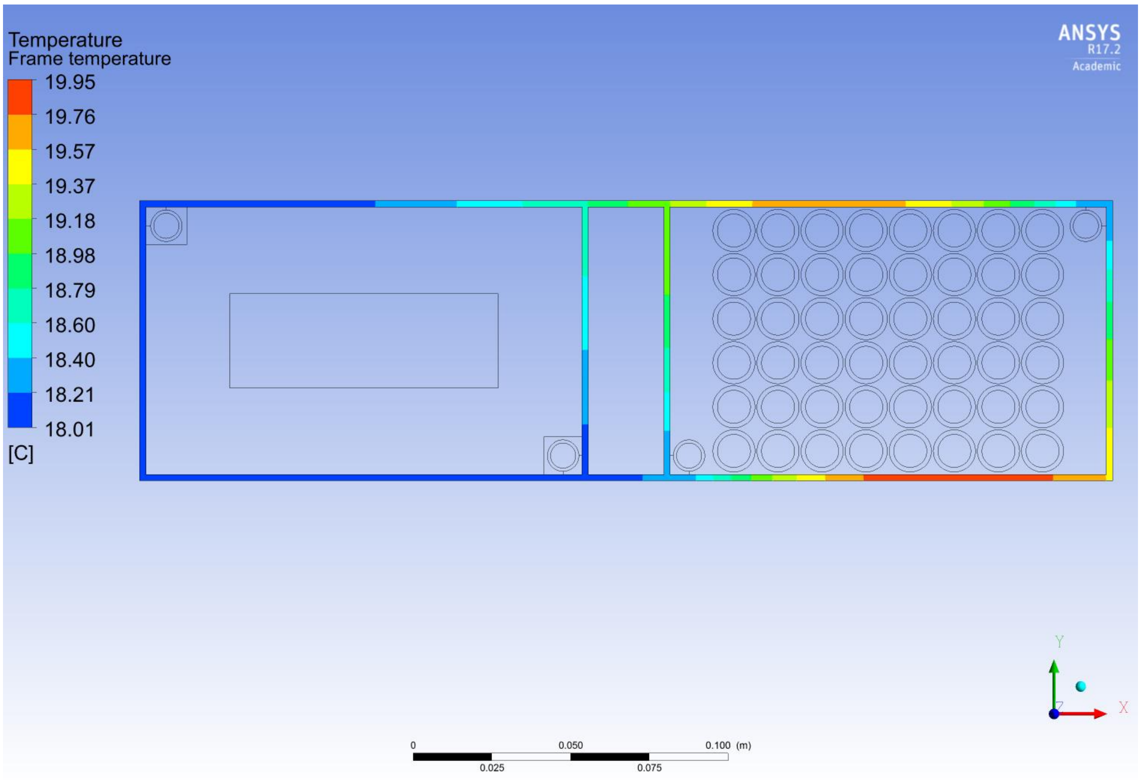

Figure 51. Temperature gradient of the frame.

In Fig. 51, the frame of the service channel only a difference of 0.01 degrees Celsius to Scenario 4 can be observed.

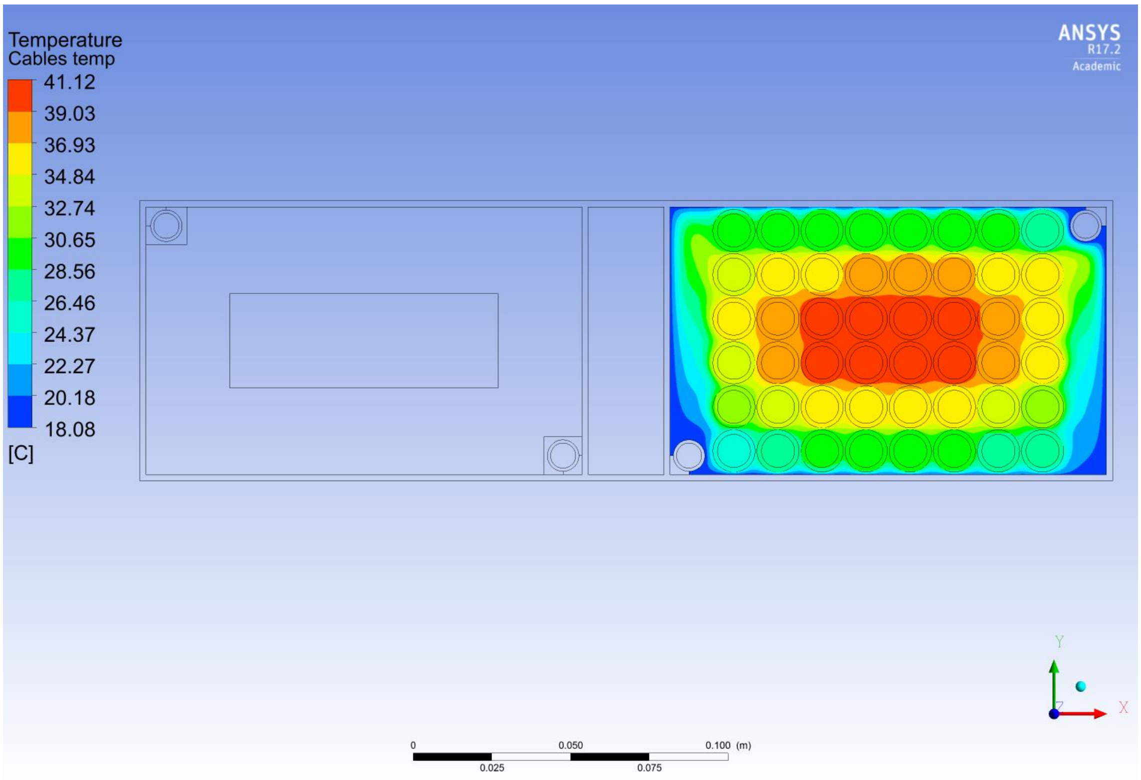

Figure 52. Temperature gradient of cables.

In Fig. 52, the cable temperatures are also almost identical with the Scenario 4.

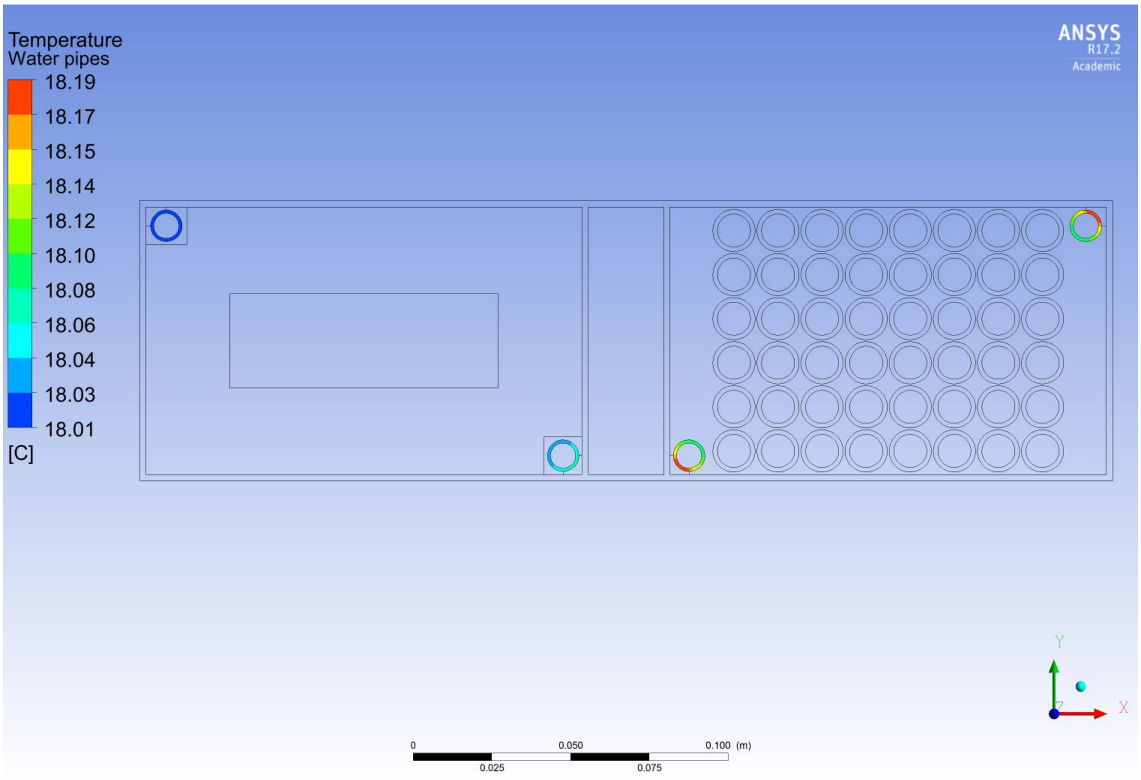

Figure 53. Temperature gradients of pipes.

Fig. 53 displays that also in the pipes almost no difference to Scenario 4 can be seen.

The lack of difference between Scenario 4 and Scenario 6 indicates that the surrounding air has very little impact on the thermal performance of a channel that has been built out of highly conductive material.

8 Conclusions

The simulations indicate that a significant difference to the overall temperatures can be made by choosing aluminum, or some other highly conductive material for the channels. By using aluminum in the simulations temperatures of the frame are stable and clearly above the dew-point. Aluminum also dropped the maximum temperatures of the cables, which is beneficial for power losses of the cables as the loss increases with temperature. When comparing the results from Scenarios 3 and 4 to scenarios 5 and 6, it becomes even more obvious that with a highly conductive material it is still possible to keep the channel temperature controllable even in extreme cases.

Although the simulations are very clear, still a real-life mockup of the channel section should be made to compare the results of the simulations to reality. A mockup would also help to improve the insulation design and help to see if such a way of insulating that was shown in the 3D models can be properly achieved in reality. Currently the cooling pipes are wrapped inside flexible Armaflex instead of solid blocks of insulation that are attached to the channel walls. This is also why the results are not directly comparable to the current design of Phase 1.

A real life mockup would also help confirming that the service distribution designed in this thesis works in reality, and if the design does not work, a real life mockup would clearly indicate where the problematic areas are.

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18. May 2017, Conversation, Nicola Bacchetta, PhD (Physics)

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22. September 2017, Conversation, Nicola Bacchetta, PhD (Physics)

23. February 2017, Conversation, Antti Onnela M.Sc.